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ACOUSTIC LIFE CYCLE ASSESSMENT OF OFFSHORE RENEWABLES – IMPLICATIONS FROM A WAVE-ENERGY CONVERTER DEPLOYMENT IN FALMOUTH BAY, UK

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Abstract: *Marine Renewable Energy is developing fast, with hundreds of prototypes and operational devices worldwide. Two main challenges are assessing their environmental impacts (especially in near-shore, shallow environments) and ensuring efficient and effective maintenance (requiring specialised ships and fair-weather windows), compounded by the lack of long-term measurements of full-scale devices. We present here broadband measurements (10 Hz to 32/48 kHz) acquired at the Falmouth Bay Test site (FaBTest, UK) from 2010 onwards, for a 16-m ring-shaped Wave Energy Converter, in waters up to 45 m deep. This period covers baseline measurements, including shipping from the neighbouring English Channel, one of the busiest shipping lanes in the world (ca. 45,000 ship transits annually) and the full period of installation and energy production, including maintenance episodes. Acoustic signatures are measured as Sound Pressure Levels (e.g. for impacts) and time/frequency variations (for condition-based monitoring via Acoustic Emissions). They change through time, depending on weather and modes of operation. Long-term measurements are compared with modelling of potential variations in this complex environment and with laboratory experiments. These are used to outline the varying acoustic contributions through the life cycle of a typical wave energy converter, yielding insights for other wave devices in other environments.*

Keywords: *Life Cycle Assessment, Acoustic Emission, Offshore Renewable Energy, Wave Energy Converter, Condition Based Monitoring.*

INTRODUCTION

Offshore Renewable Energy (ORE) has been identified as a key player in tackling the energy problems of the 21st century. From energy security, to greenhouse gas emissions, to powering isolated communities, offshore energy (including offshore wind, wave and tidal) is a significant part of the solution. It is forecast that world-wide the ocean energy industry will be worth £76 billion by 2050 also providing an economic benefit [1]. This potential is being actively pursued by the majority of coastal countries including USA, China, and Japan. The UK is a world leader in this emerging industry, with efforts focused around coastal areas such as Cornwall, Pembrokeshire and Scotland.

Two challenges currently hindering the growth of ORE are the assessment of the environmental impact of devices and the high risk and cost of effective and efficient maintenance activities. Devices are often located near to shore and in shallow depths making the acoustic impact of devices more difficult to quantify and model without data specific to that environment. Maintenance offshore traditionally relies upon specialist vessels, perfect weather conditions and significant budget, but new research suggests that continual condition based monitoring of OREs (called Acoustic Emission) could be possible in the underwater environment. Furthermore, these two applications of underwater acoustics could be realised with the same sets of data and multiple data processing techniques, doubling the value of the data [2].

Unlike other studies (eg. [3–6]), this acoustic study was conducted on a full-scale device over a period of just under 2 years, providing insight into seasonal effects upon both the underwater acoustics and the device operation. In this paper the WEC, its environment and a timeline of events are presented. An overview of the results from each period of activity (pre-installation, installation, operational/non-operational, condition based monitoring and decommission) is then provided to aid in the discussion which focuses on the “life cycle” of the device and its underwater acoustic emission.

THE WEC AT FABTEST

The Wave Energy Converter (WEC) considered in this paper is the *Bolt-2 Lifesaver* from Fred Olsen Renewables [7]. It is a doughnut-shaped floating WEC as shown in Fig. 1. The floating platform has a 16-m outer diameter and a 10-m inner diameter, with 1-m height and a mass of 55 tons. While the platform has the capacity to install 5 Power Take-Off (PTO) systems (Fig. 1b), only 3 were installed during this trial period as shown in Fig. 1a. During operation, the PTOs were moored to the seabed with a primary mooring line and a five-point secondary mooring system was attached to the device.

Lifesaver was deployed at the FaBTest facility (Falmouth Bay Test Facility, www.fabtest.com) in Falmouth, UK. Falmouth Bay is located at the western entrance to the English Channel with a large and deep natural harbour. It welcomes considerable local commercial shipping and recreational boating activities while also being located next to busy shipping lanes. The test facility itself is a 2.8-km^2 test area situated 3 – 5 km offshore as shown in Fig. 2. This nursery site is sheltered by the Lizard Peninsula from the prevailing SW wind and swell, and exposed to long fetch waves from the E-SE providing a moderate wave climate with peak tidal surface currents of ~0.8 ms^{-1}. FaBTest is supported by the University of Exeter and Falmouth Harbour Commissioners.

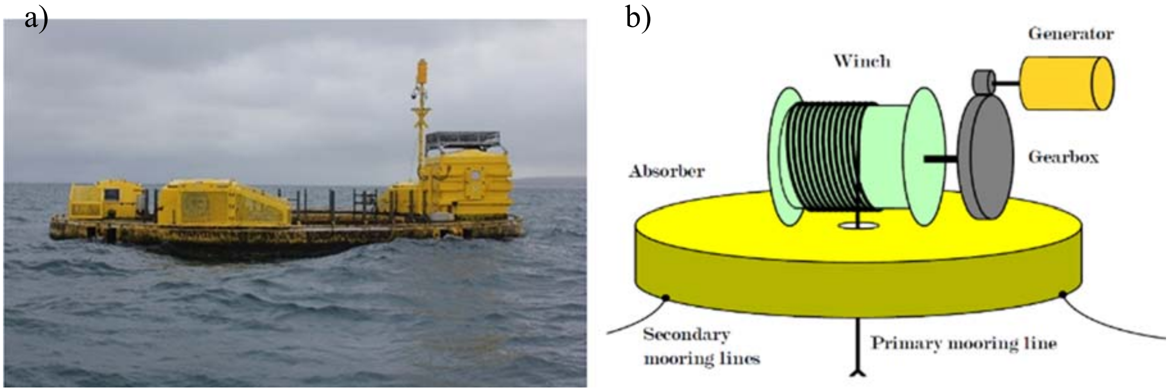

Fig. 1: a) Lifesaver on site at FaBTest, Falmouth, UK. Credit: Duncan Paul, Falmouth Harbour Commissioners, 2013. b) Power Take-Off System for Lifesaver.

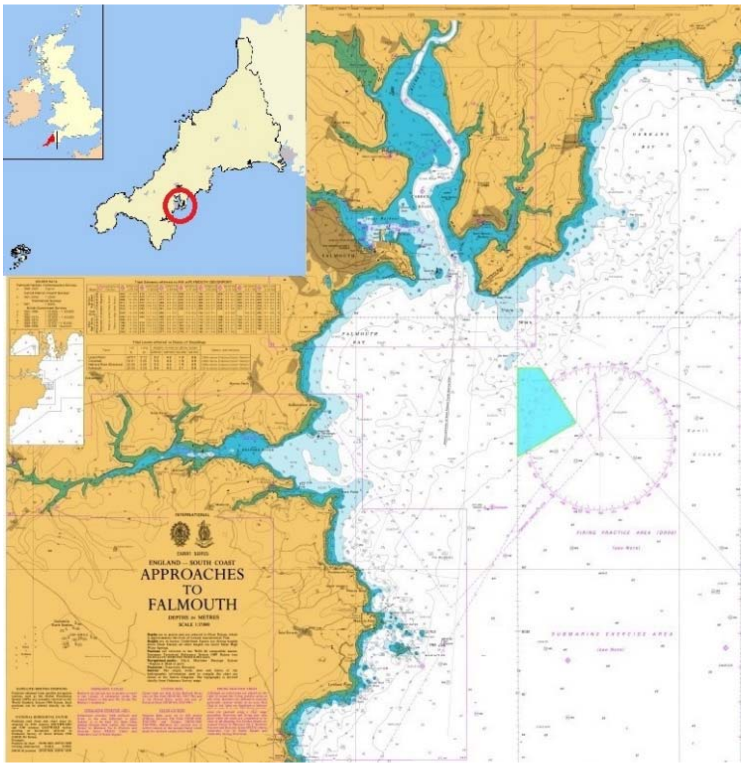

Fig. 2: Falmouth Bay Test Facility (blue) within Falmouth Bay, Cornwall, UK.

The depth of FaBTest varies from 15 m at its northern boundary to 50 m at its south-eastern boundary. The seabed varies with rock, maerl gravel, subtidal sand/gravel and subtidal sand/mud from north to south respectively [8].

To collect passive acoustic data from the WEC Autonomous Multichannel Acoustic Recorders (AMAR, Jasco Applied Sciences) was chosen for its high storage capacity (1 TB) and ease of deployment. Two AMARs were used back to back to ensure continual monitoring (while one recovered and uploading data, the other deployed). 90-day deployments took place between 13th June 2012 and 4th November 2013 (although data between 9th April 2013 and 4th June 2013 was lost). The AMARs were located 200 m from the WEC, 10 m above the seabed and in depths of 25 – 45 m. Recordings were taken for the first 30 minutes of every hour at 64 kHz allowing a frequency range of 10 Hz – 32 kHz to be collected.

The main component to the AMARs were omnidirectional hydrophones with a nominal sensitivity of -165 ± 5 dB re 1 V/µPa and 24-bit dynamic resolution. The hydrophones were calibrated before deployment and upon return with recorded accuracies of ±1.32 dB and ±0.7 dB for the 2 hydrophones. This is close to the ±1 dB operational accuracy expected in typical offshore conditions [9].

Wave data was collected from a Seawatch Mini II directional wave buoy located 150 m from the AMAR location [10]. Wave data was sampled at 2 Hz for 1024 s of every 30 minutes. This data was important to be able to correlate background ambient noise detected with in-situ wave conditions.

The AMAR was deployed from 10th March 2012 to 4th November 2013. Baseline measurements were recorded from 11th March 2012 to 25th March 2012. Installation activity was recorded from 25th March 2012 to 29th March 2012. The WEC was then in place from 29th March to 30th December 2013. Fig. 3 graphically shows this information, as well as the operational/non-operational activity of the WEC and the number of PTOs active at any time.

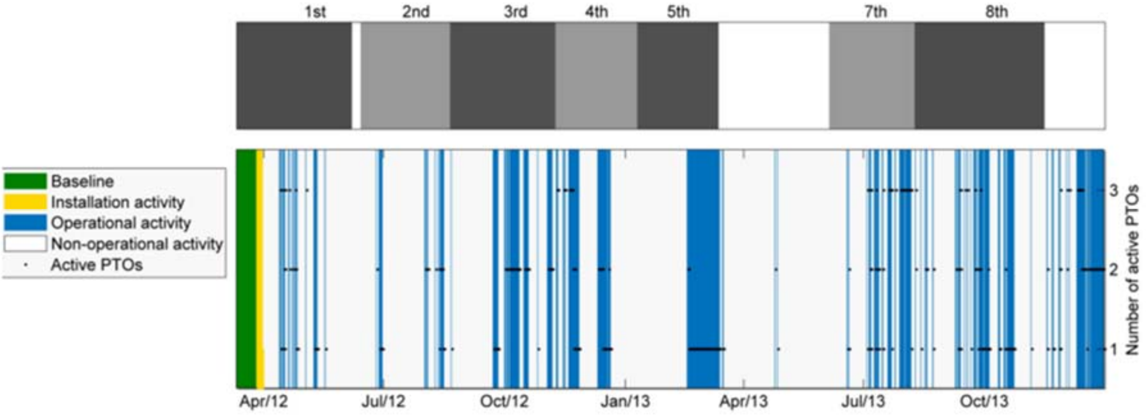

Fig. 3 Top chart shows the time periods and number of each AMAR deployment where white spaces indicate no recording. The bottom chart shows the time periods of different activity periods at the FaBTest site including baseline, installation activity and operational periods from 29th March 2012 to 30th December 2013. The number of PTOs active for each operational activity period are also shown. From [11].

RESULTS

Over the last 5 years, the University of Bath and the University of Exeter have been collaborating on projects that focus on the Falmouth Bay area. The sections below summarise the relevant measurements along with associated publications.

1.1. Pre-Installation

Before the WEC was deployed at FaBTest, a study was conducted into the noise from shipping in the Falmouth Bay area [12]. Merchant concluded that the shipping could be separated into two distinct groups, low frequency sound from distant shipping of a stable nature, and a higher amplitude and variable component from local vessel activity. By separating the two during analysis using an adaptive threshold to the Sound Pressure Level (SPL), the absolute and relative Sound Exposure Levels (SELs) of shipping could be described. In the frequency range 0.01 – 1 kHz the 24-hour absolute SEL was 157.0 dB re 1 μPa^2 s compared to an estimated 142.6 dB re 1 μPa^2 s in the absence of intermittent shipping noise.

The study of the *Lifesaver* WEC began with a "baseline period" that lasted 2 weeks, before the installation of the device at FaBTest. It was found that mean 30-minute sound levels ranged from 34 dB re 1 Pa^2 Hz^{-1} at 47,964 Hz to 113.4 dB re 1 Pa^{2}Hz^{-1} at 76 Hz.

Results from [11] suggested that Falmouth Bay (classed as having high anthropogenic activity) is overall quieter than other similar published sites which could be due to reduced contribution from distant shipping given the shape of Falmouth Bay.

Sources of noise were found from Shipping, sonar like sounds and snapping shrimp during the 2-week pre-installation period.

1.2. Installation

The "installation period" lasted 5 days and includes all activities that were associated with the installation of the WEC at FaBTest, including, but not limited to the presence of work vessels and the laying of anchor chain. No drilling or pile driving was required, and hence the WEC is classed as having minimal installation requirements. This technique is typical for attenuator/point absorber devices that float on the sea surface [13]. Installation activity was noted during 20% of the recording from during the 5-day installation period.

Installation activity was found to increase sound levels by a mean difference of 6.9 dB between the installation and pre-installation activity periods in the frequency range 10 Hz - 48 kHz (comparing like for like data in terms of wave conditions). The lowest frequency ranges (10 – 100 Hz) was found to exhibit the greatest difference (of nearly 20 dB) between pre-installation and installation periods, but the loudest received levels were recorded in the frequency range of 100 Hz - 1 kHz.

1.3. Operational and Non-Operational Periods

The WEC was non-operational (ie. inactive and not producing power) during high and extreme wave conditions (to reduce the risk of damage to the WEC) as well as during low wave conditions where it shut down at wave heights 0.4 - 0.6 m H_s [14].

Sound metrics during these periods were calculated over long time periods (either an entire deployment or several deployments) due to the inability to identify differences over a few days. Comparing operational and non-operational broadband SPL_{RMS}s are inconclusive with some deployments indicating louder overall levels during operational activity and some during non-operational activity. This indicates that there is no overall effect of the WEC on the broadband SPL_{RMS}s at this location which is likely due to the many other sources of noise in Falmouth Bay. From 10 Hz to 32 kHz the mean difference between median PSD levels during operational and non-operational activity was just 0.04 dB. However, this was higher between 10 Hz - 100 Hz where the mean difference was great than 0.46 dB.

This low level difference has been previously noted for Wavestar and attributed to moving parts being located above the sea surface [5], although this particular conclusion was drawn from only 57 minutes of data.

1.4. Condition-Based Monitoring

Acoustic Emission is a long-used technique for Condition-Based Monitoring (CBM) of moving parts but recently work has explored using this technique underwater and utilising the low attenuation of sound in water as a sound propagating tool, allowing for a remote sensing technique.

The operational status and “log book” from the device developers was matched to the 30-minute acoustic files and engineering features were able to be identified.

The acoustic signature in Fig. 4 is the active PTO system during WEC operation. There are 0.5-s bursts up to 90 dB re 1 µPa^2 Hz^{-1}, mostly between 100 Hz and 1 kHz. The three peaks in this signal correspond to vibrations in the primary mooring system induced by high sea states. Their period is approximately 6 s, matching the period of oscillations in the primary mooring. Tonal components at 30, 60, 80 and 100 Hz, reaching 90 dB re 1 µPa^2 Hz^{-1} are also attributed to the device generator. This processing required very detailed time frequency analysis of the data, which in this case was visually inspected. This signature was only detected when averaged measured wave heights were above 0.9 m, the minimum needed for the operation of the device.

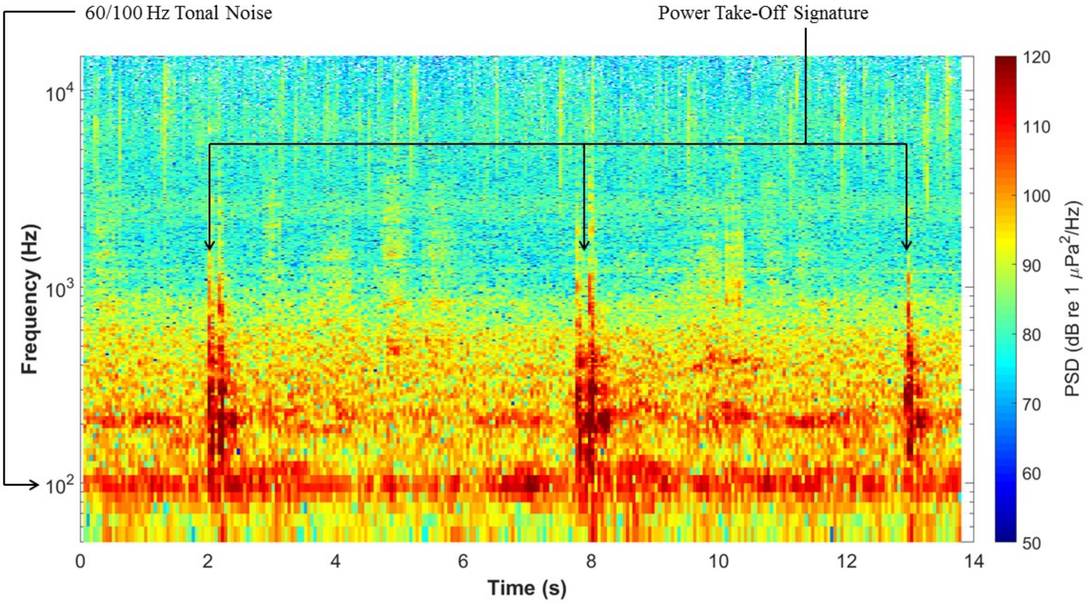

Fig. 4: Typical acoustic signature identified due to the Power Take Off of Lifesaver WEC. The STFT plot (31.25 Hz frequency bandwidth, 50% overlap, flat shading) shows variations in frequencies with time, and the colour coding details the relative magnitude of the power spectrum.

1.5. Decommission

Although this data does not include recordings from the decommissioning period of the WEC at FaBTest, it can be assumed to be similar to the installation period. The use of vessels, movement of anchors and other equipment would be almost identical during installation and decommission for this WEC and therefore the acoustic signatures can be assumed to be very similar.

DISCUSSION AND CONCLUSION

Each period of activity for the WEC has different acoustics properties that are of interest and therefore multiple processing techniques are required to fully understand the data. Table 1 shows the activity periods and the length of time data was collected for. It also states the timescale of interest when processing the data for trend and feature identification. For example, pre-installation the timescale of most use for processing was 24+ hours for SEL calculations. During installation, intermittent periods of vessel activity led to feature identification on a timescale of minutes. To understand the overall effects of operational activity of the WEC, processing took place over entire deployments of ~90 days. This is in stark contrast to the processing periods for condition based monitoring where very detailed time-frequency analysis was required to extract features relating to engineering processes.

Activity Period/Purpose	Length of time data collected for	Timescale for data processing trend identification	Relevant data
Pre-installation	2 weeks	Days	All
Installation (& Decommission)	5 days	Minutes	20%
Operational/Non-Operational	~90 days per deployment	90+ days	See Fig. 3
Condition Based Monitoring	~90 days per deployment	< Seconds	All

Table 1: Timescales used for the identification of trends within different periods or purposes of data from the WEC at FaBTest.

A few authors have identified interesting engineering features within acoustic data such as in the Lysekil Project where an incorrectly assembled WEC jut 20 m from the recording equipment was found to be the cause of high frequency, high amplitude bursts of sound that were clipped [6]. Recordings from the Pelamis device (at 333 m distance) included “clanking”, “banging” and a “rattling” noises that occurred throughout the data set [3]. In both cases, no direct link was made between the signatures found and the possibility of underwater acoustic emission CBM.

The life-cycle of a WEC has not previously been studied in detail, especially the acoustic properties. This study presents long term acoustic monitoring of a WEC from pre-installation to decommission and the key acoustic properties and features identifiable during these periods. The largest difference in sound level was between pre-installation and installation periods, where sound levels increased by a mean difference of 6.9 dB in the frequency range 10 Hz - 48 kHz. The difference between operational and non-operational periods was small, with the mean difference between median PSD levels just 0.04 dB (10 Hz to 32 kHz) and 0.46 dB comparing just low frequencies (10 Hz - 100 Hz). However, on the short time scales required for condition based monitoring, significant 0.5-s bursts up to 90 dB re 1 $\mu Pa^2\ Hz^{-1}$ are detected mostly between 100 Hz and 1 kHz.

Future work will focus on the modelling of the signatures found here to understand their propagation properties in a shallow underwater environment.

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