Monitoring the condition of Marine Renewable Energy Devices through underwater Acoustic Emissions: Case study of a Wave Energy Converter in Falmouth Bay, UK

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Abstract

Maintaining the engineering health of Marine Renewable Energy Devices (MREDs) is one of the main limits to their economic viability, because of the requirement for costly marine interventions in challenging conditions. Acoustic Emission (AE) condition monitoring is routinely and successfully used for land-based devices, and this paper shows how it can be used underwater. We review the acoustic signatures expected from operation and likely failure modes of MREDs, providing a basis for a generic classification system. This is illustrated with a Wave Energy Converter tested at Falmouth Bay (UK), monitored for 2 years. Underwater noise levels have been measured between 10 Hz and 32 kHz throughout this time, covering operational and inactive periods. Broadband MRED contributions to ambient noise are generally negligible. Time-frequency analyses are used to detect acoustic signatures (60 Hz – 5 kHz) of specific operational activities, such as the active Power Take Off, and relate them to engineering and environmental conditions. These first results demonstrate the feasibility of using underwater Acoustic Emissions to monitor the health and performance of MREDs.

Keywords

Underwater Acoustics; Acoustic Emission; Condition Monitoring; Health Monitoring; Marine Renewable Energy; Wave Energy Converter.

1. Introduction

Marine Renewable Energy Devices (MREDs) are potential future contributors to the global energy mix and associated reductions in greenhouse gas emissions, as acknowledged in the UK [1] and through international policies (e.g. [2,3]). Latest UK reports show for example that 20% of the UK's current electricity demand could be met using tidal stream devices and Wave Energy Converters (WECs) [4]. Their contributions to energy production are expected to grow annually by 15.2% on average until 2030 [5]. However, their use is limited by technological obstacles and the high costs associated with Operation & Maintenance (O&M) activities.

Tidal stream devices and WECs have not yet converged to unified designs, unlike for example the three-bladed horizontal-axis turbine design of the wind industry. For WECs alone, 1,000+ patents have been allocated across North America, Japan and Europe [6], covering 9 main categories [7] and making a standardised approach to O&M more problematic. MREDs are expected to work in harsh oceanic environments, in which extreme weather may damage or cause the failure of devices [8] (improving the survivability of devices is another area of current development within the WEC industry). Also, typical weather conditions make marine intervention more difficult or impossible [9] (WECs are for example located in the areas where large waves are expected for long periods of time). This is compounded by the high costs associated with O&M, using specialised ships and highly skilled labour which might not always be readily available, potentially increasing any downtime. MREDs must therefore be reliable, robust and maintained effectively to reduce the likelihood of unexpected downtime and maintenance. These economies can then translate into more energy generated over longer periods, at lower costs.

Reactive O&M involves operating a device until failure occurs, resulting in unscheduled downtime and requiring prompt reaction. It was adopted in the early years of the wind industry, increasing O&M

costs to 25% of the total incomes generated by offshore wind turbines [10]. Analyses of 750 onshore turbines in 1989-2005 showed for example that 75% of the annual downtime was caused by just 15% of the failures [11]. These figures are expected to be more severe for offshore wind turbines, because of their harsh marine environments, with longer downtimes due to the difficulties of access. For this same reason, MREDs are also likely to encounter severe downtime statistics. Preventive maintenance, with regular inspections and systematic part replacements, can reduce these costs, but it still requires regular downtime and potentially unwarranted replacements of expensive components [12]. Condition-based maintenance is a more efficient and cost-effective approach, scheduling O&M activities based on the actual system health [12]. It traditionally includes *in situ* tools such as vibration and oil temperature monitoring, and Acoustic Emissions (AE) from the entire devices, or areas of interest [13].

This article investigates the use of AE to remotely monitor an actual WEC device, in this case Fred. Olsen's "*Bolt-2 Lifesaver*" during its two-year deployment in Falmouth Bay, UK. It should be noted that the entire long-term monitoring data set has been analysed in two publications that focus on the environmental impacts [14,15]. The purpose of the paper is to explore whether engineering features can be detected within that data set. As such, the scope of the paper is intentionally limited to the detection of engineering features.

The structure of the paper is as follows. Section 2 will review expected AE sources in offshore devices, focusing on WECs but adaptable to tidal stream turbines and other MREDs. Section 0 will present the WEC device under consideration, the supporting data (acoustics, environmental and engineering) and the general methodology. Section 4 will show the general contribution of this WEC to the ambient noise levels over its period of activity, comparing operational and non-operational periods, and identifying specific AE from parts of the WEC, in this case the Power Take-Off (PTO). Section 5 will discuss these results, comparing with other published data, identifying the strengths and limits of this approach and showing how it can be extended to other WEC designs. The use of underwater AE, in specific frequency bands, is potentially capable of reducing O&M costs and increasing WEC reliability, hence improving the viability of this industry as a significant contributor to energy production.

2. Acoustic Emissions from Marine Renewable Energy Devices

The release of energy within materials, associated for example to wear and tear of components or to part failure, generates sound waves, propagating in solids and/or fluids. Their use forms the basis of Acoustic Emission analyses, well documented for devices on land (e.g. British Standards [16]) and mostly associated with frequencies between 1 kHz and 1 MHz (e.g. [17]). Their monitoring is performed on the devices themselves or remotely, either in the near field or in the far field, although the latter is limited by the strong attenuation of sound in air (14–4,000 dB/km in the best conditions) [18]. Underwater environments are better suited to remote monitoring, with attenuations in seawater of a few dB/km at the same frequencies and hence received levels will be mainly reduced through the spreading losses caused by sound propagation [18]. This allows: locating sensors away from the device under consideration, detecting AE from different parts, and, because MREDs are intended to be deployed in large arrays, each sensor could in theory detect AE from multiple devices, as well as monitor their environmental impacts. However, underwater ambient noise will be of a larger consideration than in air, so limitations do exist to the practicalities of underwater AE.

Underwater noise generated by MREDs varies with device design, their mode of use and the prevailing environmental conditions. It is also modulated by the local settings (bathymetry, seabed composition and sound speed profile). Recent syntheses (e.g. [19]) showed that MRED noise extends up to a few hundreds of kHz at most. Long-term noise sources during operation can include components of the device itself, its mooring, movements of air or water (e.g. slapping waves on a hull), all of which might be offset by the surroundings, from weather-related noise (waves, wind and precipitation) to shipping or animal life.

Estimates of AE levels and frequencies expected from MREDs can be informed by work done in air (and sometimes in water) for their individual components. Early work on breaking wire ropes . Events (a number of counts associated with the same cause) increase with the size of different types of defects in bearings. Evidence of degradation within gearboxes produced similar acoustic results [20] showed for example that AE frequency ranges extend from 25 kHz to hundreds of kHz in some cases. Investigations of wire fracturing in air identified frequencies of 0-100 kHz [21], with narrow-band peaks for individual breaking events, of amplitudes varying with the extent of the damage to the wires. The breaking of epoxy-based composite fibres in air showed similar results [22], with sound levels reaching 40-100 dB re 20 µPa (broadband kHz range). Rolling element bearings can produce both impulsive and continuous emissions across a wide frequency range (up to 2 MHz), which can in turn be related to the geometry and speed of the bearing [23–25][26–28], with high frequency (up to 1 MHz) impulsive and tonal AE components. Peak amplitude, root-mean-square Sound Pressure Levels (SPL_{RMS}) and ring down counts (the number of times a burst signal crosses the detection threshold) all increased with defect sizes [26–28], whereas SPL_{RMS} increased with the misalignment of gears [29]. Moreover cavitation in air within a pump produces a continuous broadband spectrum (20 Hz – 20 kHz) [30], and incipient cavitation increases SPL_{RMS} and peak amplitudes [30,31] and comparable results were found underwater for a wider frequency range (0.1 Hz – 100 kHz) [32].

Table I: Quality matrix of AE of components relevant to underwater AE techniques (from [33]).

Mechanical part	**Fault details**	**Frequency range**	**Emission**	**General findings**	**References**
Rolling Element Bearing (Ball bearing & cylindrical bearing)	Natural and seeded defects located in multiple locations of bearings	In air 100 kHz – 2 MHz	Impulsive and continuous components	Increase in ring down counts and energy with defect size.	[23,24]
				SPL_{RMS} and peak amplitude increased with defect size for rough, point and line defects.	[25,26]
				Ability to detect faults 0.3 m from bearing.	[34]
Gearbox	Pitting and scuffing of gear tooth	In air 100 kHz – 1 MHz	Impulsive and continuous components	Increase in SPL_{RMS} with defect size and due to misalignment.	[26,27]
				Increase in (wideband) amplitude and Ring down counts with defect size.	[27,28]
Pump	Incipient and developed cavitation	In air 5 Hz – 20 kHz	Continuous	Minimum noise at best-efficiency point of the pump, due to minimal flow turbulence.	[30,31]
				Cavitation produces broadband acoustic spectrum.	[30]
				Increase in SPL_{RMS} and peak amplitude with cavitation onset.	[30,31]
		Underwater 0.1 Hz – 100 kHz	Continuous	Frequencies < 8 kHz contained mechanical noise.	[32]
				Noise signal was a better parameter to sense the occurrence of cavitation (than traditional methods).	[32]
Rope	Fibre and wire rope fractures and breaks	In air 100 kHz – 600 kHz	Impulsive	1-to-1 correlation between AE events and broken fibres/wires.	[21,22]
	Wire rope breaks	In air *through* water 1 kHz – 200 kHz	Impulsive	Wire breaks detected remotely.	[20]
				No information at frequencies < 25 kHz due to non-propagation of shear waves in water.	[20]

These results are summarised in Table I but they are intended as possible trends only: AE frequencies in air might not be the same once measured underwater, some studies used direct monitoring (e.g. with sensors upon gears or on the gearbox) and shear waves (when present) would not propagate underwater. Finally, some components like bearings and gearboxes, might be fixed above water in

WECs, or be separated from direct water and therefore produce only airborne sound. In the case of remote sensing, frequency-dependent attenuation and the competition with other sound sources (from other MREDs, weather, shipping and animal life) might also affect the relevance of these results. The next section will therefore present field measurements from a full-scale WEC in a complex environment, based on a monitoring period of 2 years, to identify which AE elements are the most promising in real conditions.

3. Case study of a WEC in Falmouth Bay (UK)

3.1 The Wave Energy Converter and its environment

Falmouth Bay (Cornwall, UK) is a large and deep natural harbour at the western entrance to the English Channel. It is close to busy shipping lanes and also welcomes considerable local commercial shipping and recreational boating activity, whose noise contributions were presented in [35]. The Falmouth Bay test facility (*FaBTest: www.fabtest.com*) is a 2.8-km^2 test area supported by the University of Exeter. It is situated within Falmouth harbour, 3-5 km offshore. By being in the lee of the Lizard Peninsula, it is sheltered from the prevailing SW wind and swell, and exposed to long-fetch waves from the E-SE. This moderate wave climate, with peak tidal surface currents of ~ 0.8 m/s, make it an ideal “nursery” site to test MREDs and in particular WECs [36].

In March 2012, Fred. Olsen (FO) Ltd. deployed and trialled an electro-mechanical WEC at the *FaBTest* site [37] to gain operational experience of the device and investigate its performance over a total period of more than 2 years. This WEC, named ‘*Bolt-2 Lifesaver*’, is a doughnut-shaped floating device (Figure 1). The flotation platform has a 10-m inner diameter, 16-m outer diameter and 1-m height with a mass of 55 tons. The flotation platform has the capacity to install five Power Take-Off (PTO) systems, but only three were installed during the trials, as shown in Figure 1. During operation, the PTOs were moored to the seabed and a five-point secondary mooring system was attached to the device. The WEC was redeployed to Hawaii in March 2015.

Figure 1: *Lifesaver* on site at *FaBTest*, Falmouth, UK. Credit: Duncan Paul, *Falmouth Harbour Commissioners*, 2013

3.2. Acoustic monitoring

Passive acoustic monitoring of the WEC and its environment has been continuous during all stages of installation and operational activities of the WEC [14,15]. Autonomous Multichannel Acoustic Recorders (AMAR Generation 2, from Jasco Applied Sciences) were used, due to their high storage capacity (1 TB) [38], suitable for long periods of recording, and for their ease of deployment. Two AMARs were used in turn: when one was recovered and uploading data, the other was deployed in its place, ensuring continuous monitoring during successive 90-day deployments between 13 June 2012 and 4 November 2013 (the data between 9 April 2013 and 4 June 2013 was however lost during recovery). The AMARs were placed approximately 200 m from the WEC [14,15] ~ 10 m above the seabed at water depths of 25-45 m. For a detailed representation of the AMAR deployment, please refer to Garrett [14]. They measured ambient sound levels for the first 30 minutes of every hour, sampling at 64 kHz (and therefore accessing a frequency range of 10 Hz to 32 kHz). Each AMAR was based around an omnidirectional hydrophone (GeoSpectrum M8E), with nominal sensitivity of -165 ± 5 dB re 1 V/µPa and 24-bit dynamic resolution. Each hydrophone was calibrated by the manufacturer before deployment (2012) and upon return for servicing (2014), and after the last deployment with a pistonphone (GRAS type 42AC). Accuracies were ± 1.32 dB and ± 0.70 dB respectively, very close to the ± 1 dB operational accuracy expected in typical conditions and fully in line with good practice recommendations from [39].

Falmouth Harbour is a busy commercial port, with more than 1,000 ship arrivals in 2012 and substantial recreational boating [15], both of which contribute to high levels of background noise [35]. The distance from the WEC to the hydrophone (~ 200 m) is considerably larger than distances between sensors and components typically monitored in AE studies (Section 2). It is therefore logical to question whether AE from the different components of the WEC can be reliably detected at these ranges. Spherical spreading loss is calculated as:

$$RL = SL - 20logR \quad \text{Eq. (1)}$$

where RL is the received level in dB, SL is the source level in dB and R is the distance of the receiver from the source in m [40]. Boundaries, such as the sea surface and seabed in shallow water, act as reflective surfaces and reduce the spreading loss. Where this occurs, cylindrical spreading is calculated as:

$$RL = SL - 10logR \quad \text{Eq. (2)}$$

where RL is the received level (dB), SL is the source level (dB) and R is the distance from the source (m) (Richardson et al. 1995). Absorption loss also occurs which increases with frequency:

$$a = 0.036\, f^{1.5} \quad \text{Eq. (3)}$$

where *a* is the absorption coefficient (dB km^{-1}) and *f* is the frequency (kHz) [41]. Transmission loss resulting from cylindrical spreading (as expected in shallow water) and absorption loss is given in Fig. 2. There is between -20 and – 25 dB transmission loss at 200 m at all frequencies presented (10 Hz – 100 kHz). Therefore, AE signals from a WEC 200 m away at expected source levels are considered likely to be detected over background noise and suitable for condition monitoring purposes.

Figure 2 also shows a wave buoy, at which wave heights were measured. This Seawatch Mini II directional wave buoy [42] was deployed approximately 150 m from the AMAR location [43]. Its measurements were sampled at a frequency of 2 Hz for 1024 s (17 min 4 s) every 30 minutes and used for assessment of environmental contributions to noise and for comparison with WEC operational activity [14,15,44].

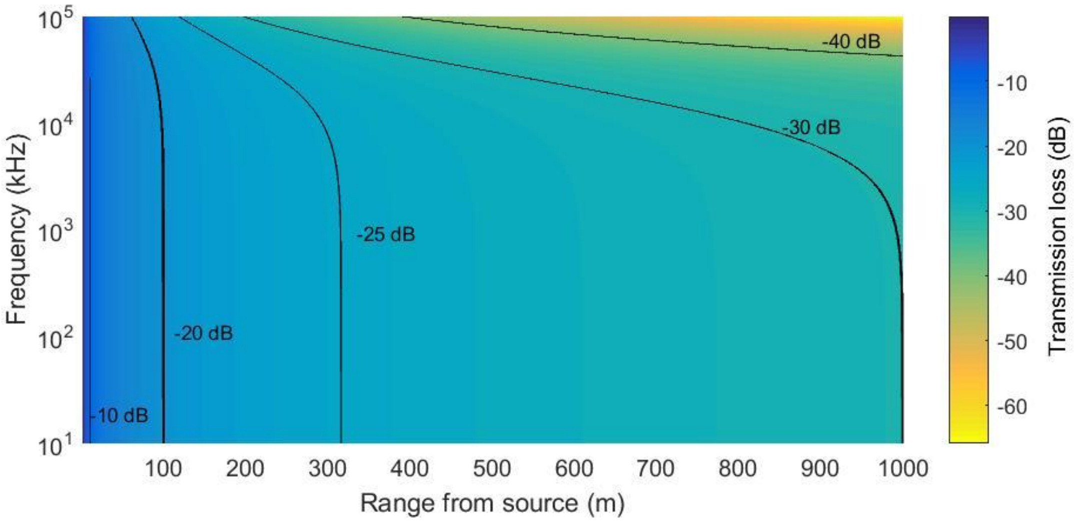

Figure 2: Transmission loss at ranges 1 m - 1,000 m from the source, assuming cylindrical spreading (Eq. 2) and standard absorption (Eq. 3), at frequencies 10 Hz – 100 kHz

3.3 Data analysis

The data has been analysed from two different perspectives: (1) average increases in noise which can be attributed to the WEC; (2) extraction of acoustic features which can be related to AE from the WEC. The former averages the data to understand the overall effect that the WEC has upon the local soundscape, whereas the latter requires analyses of both short time series and detailed frequency contents.

Average noise increases were analysed for each 30-minute recorded file, which was assigned either operational or non-operational activity. Operational activity was considered to occur when one or more PTO systems were active and producing power as recorded by the device developer [14]. Each file was processed in 1-minute samples. The raw data was processed to calibrate the data with the frequency dependent hydrophone sensitivity per 1 Hz, interpolated from values provided by the manufacturer. The processing used Fast Fourier Transforms (FFT) of 1-second windows, Hann window filter and 50% overlap, in line with good practice recommendations [39]. This processing yielded median Power Spectral Density (PSD) levels per 1 Hz for each 30-minute recorded period.

AE signals are non-stationary and often comprise overlapping transient waves, with distinct frequency contents varying with time. Short-Time Fourier Transforms (STFT) were used to produce spectrograms (like the one shown in Figure 7). Time is represented along the horizontal axis, frequency along the vertical axis, and STFT-derived PSD are colour-coded. STFT windows will show different features according to their sizes: large windows provide good frequency resolution but poor time resolution, whereas small windows provide the opposite. Multiple window sizes were tried during these analyses to best identify and characterise acoustic features related to AE from the WEC.

4. Results

4.1 Average noise contributions from the WEC

AMAR recordings cover the time span two weeks before the WEC installation and can be compared to earlier studies of background noise levels, e.g. from shipping, in the exact same area [35]. The highest sound levels in this study were recorded during installation activities, with a median PSD difference of 8.5 dB re 1 μPa^2 Hz^{-1} in the frequency range 10 Hz – 5 kHz [14]. Noise from local shipping was predominant [14] and often masked the sounds from the WEC, whose operational activity could still be detected in the absence of shipping. “Effective” source SPL_{RMS} , back-propagated to a distance of 1 m from the WEC [14], were found to be to 155 dB re 1 μPa^2 Hz^{-1}. The calculated mean difference between operational and non-operational median PSD was 0.04 dB re 1 μPa^2 Hz^{-1} in the frequency range 10 Hz

– 32 kHz, meaning that average sounds from the WEC are undetectable above background noise, at least at the 200-m range [14]. While the WEC does produce distinct sound signatures, the overall PSD between operational and non-operational states when considering long-term averages (as typically performed in environmental assessments) are often masked by other sources.

Comparison of operational and non-operational sound levels (Figure 3) however shows more important differences in the frequency range 30-100 Hz, peaking at 47 Hz (although the peak frequency varied slightly for each deployment). These differences appear small overall (less than 1 dB) but further analyses reveal more significant differences.

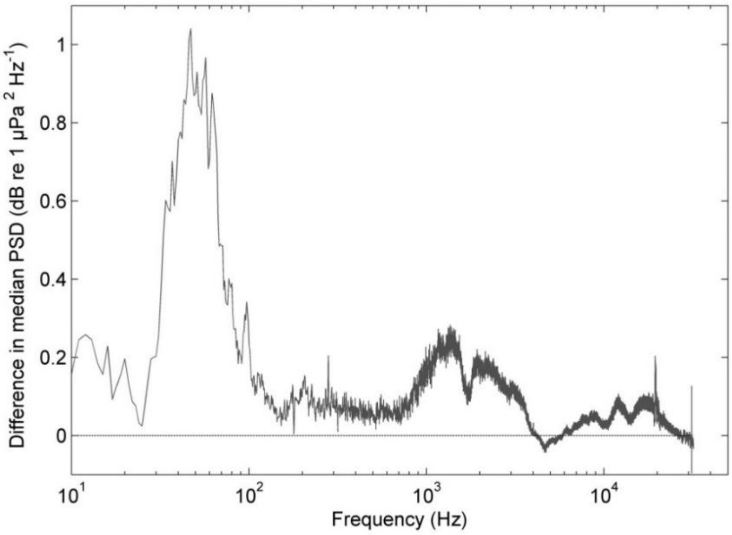

Figure 3: Difference in the overall median sound levels (June 2012 – November 2013) between the operational and non-operational activity periods of the WEC. Positive values indicate louder median sound levels during operational activity at that frequency.

4.2 AE-related acoustic features

The operational status from the device developer was matched to 30-minute acoustic segments (Section 3.3) and tonal noises were regularly identified at multiple frequencies (Figure 4). The spectrum shows high-amplitude tones at 30 Hz and 60 Hz, respectively 18 dB and 25 dB above the spectrum for conditions where the device was not operational. A marked difference can be observed in comparison to Figure 3. This is due to the large difference in shown time period. Figure 3 displays 18 months of averaged data, whilst Figure 4 shows the operational characteristics of the WEC for a 30 min time period.

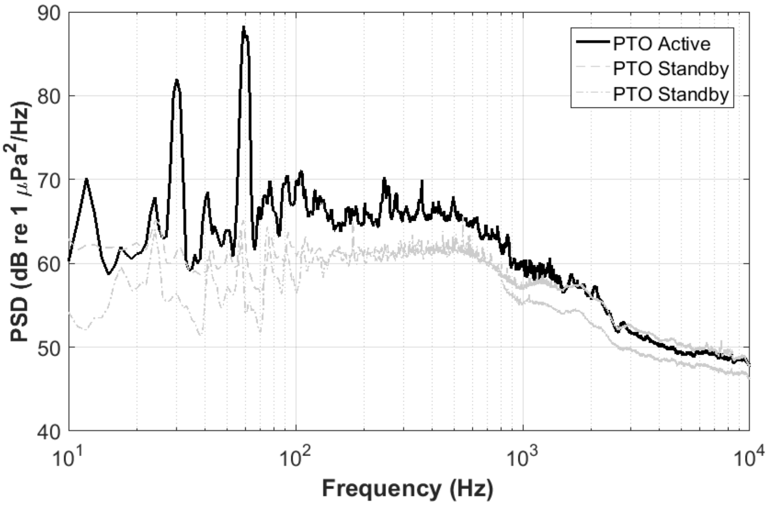

Figure 4: Power spectral density (1 Hz frequency resolution) for a typical 30-minutes acoustic segment when the WEC was operational and the Power Take Off (PTO) system was active and on standby (device not active).

The authors have been given access to the detailed operational log book from Fred Olsen Renewables for a period of time where both acoustic and environmental data were available. This allowed the exclusion of data where maintenance vessels were on site, as well as verification of the operational conditions after the acoustic data analysis. A list of relevant segments of 30 minute observations is presented in Table II.

Table II: Selected acoustic recordings, comparing with the PTO status [37] and measured wave parameters [40]: H_{m0} – Average wave height; H_{max} – Maximum wave height; T_p – Spectral peak period.

Acoustic recording	**PTO status**	**Wave parameters (representative of 30 minute period)**			**Observations**
Date/Time		**H_{m0} (m)**	**H_{max} (m)**	**T_p (s)**	
2012-08-11 19-00-00	Active	1.02	1.56	5.96	Active PTO signature Tonal: 60, 80 & 100 Hz
2012-08-11 20-00-00	Active	0.94	1.41	7.32	Active PTO signature Tonal: 100 Hz
2012-08-11 21-00-00	Active	0.94	1.25	5.37	Active PTO signature Tonal: 60 & 100 Hz
2012-08-11 22-00-00	Active	0.86	1.41	5.57	Active PTO signature Tonal: 60, 80 & 100 Hz High ship noise
2012-08-12 00-00-00	Active	0.63	0.94	5.66	No PTO signature Tonal: 60 & 100 Hz
2012-08-12 01-00-00	Standby	0.63	0.94	5.47	No PTO signature No Tonal noise
2012-08-12 02-00-00	Standby	0.54	0.94	5.37	No PTO signature No Tonal noise
2012-08-12 03-00-00	Standby	0.55	0.94	5.57	No PTO signature No Tonal noise
2012-08-12 04-00-00	In-Active	0.55	0.78	5.37	No PTO signature No Tonal noise
2012-08-12 05-00-00	In-Active	0.55	0.94	5.57	No PTO signature No Tonal noise

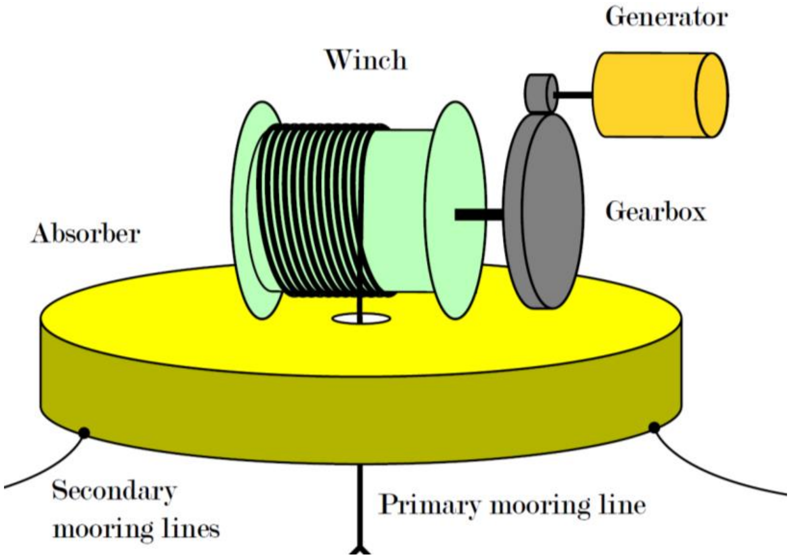

Figure 5: Schematic for Power Take-Off (PTO) system and primary mooring line [37]. Reproduced with permission from the author.

The observations are related to the status of the Power Take-Off (PTO) system, the main component of the WEC (Section 3.1), and to the wave parameters. The PTO's working principle is described in [37]: it basically consists of a winch and rope system (Figure 5), with a primary and a secondary mooring line. Samples of the spectrograms and the individual sound files outlined in Table II are available as supplementary data to this paper. A combination of gear-boxes and a pulley system converts linear motion into rotational motion and finally into electrical power through a generator. They are thought to be the causes of the tonal noises seen in the AE measurements (Figure 5, Table II).

Engineering assessments of the PTO showed it operated successfully during the 2-year deployment, although some oscillations were initiated at production saturation level [37]. At high sea states, the PTO winch and floater underwater produced rapid movement. When active, the PTO was tightly moored to the seabed: the floater and primary mooring system exerted forces in opposite directions. When waves were high, the belt-winch hit the end stop, leading the tightly moored belt and floater to produce rapid vibrations (Figure 6). This is believed to be caused by the dynamic response of the primary mooring, resulting in an aggregate system response [37].

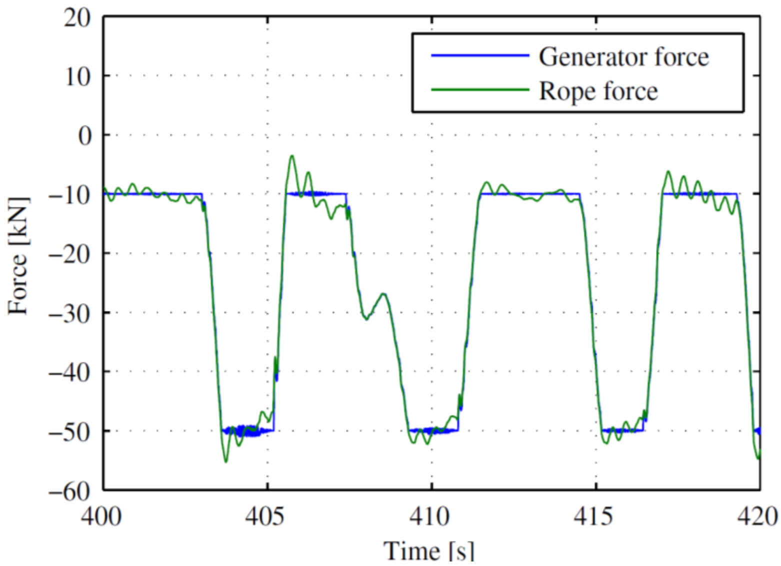

Figure 6: Oscillations encountered in primary moorings due to system dynamics [37]. Reproduced with permission from the author.

Spectrograms of individual events further show their acoustic signatures (Figure 7). Figure 7 was created with a window size of 2048 data points, corresponding to a frequency resolution of 31.25 Hz. High amplitude events (up to 90 dB re 1 μPa) last for approximately 0.5 second, spanning frequencies between 100 Hz and 1 kHz. These events occur regularly, with a period of approximately 6 seconds matching the periods of oscillations in the primary moorings (Figure 6). The regular, small variations in force (Figure 6) are directly visible as distinct AE signatures (Figure 7). They are attributed to the belt-winch hitting the end stop of the WEC at high sea states. Full analysis (Table II) shows this PTO signature is only detected when averaged measured wave heights reach above 0.9 m, as this is the 'cut-in' wave height of the device. Spectrograms such as Figure 7 also show tonal components centred on 100 Hz and intermittently between 200 – 300 Hz. This acoustic behaviour has been observed throughout the data recordings (Table II) and is understood to be acoustic signature of the PTO generator.

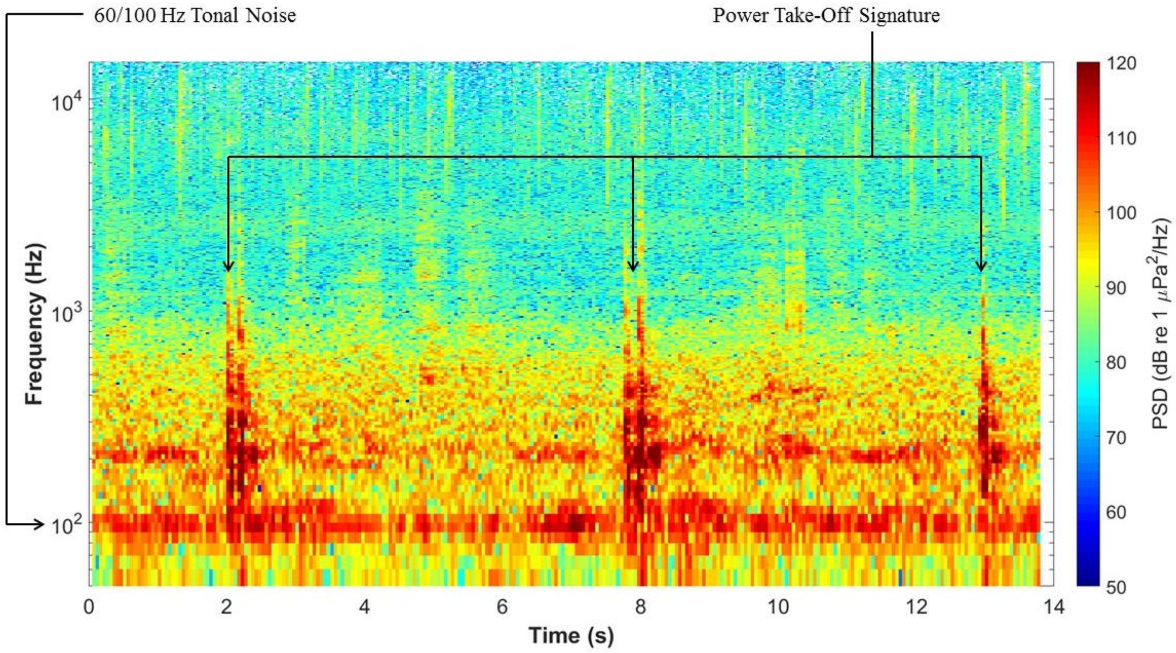

Figure 7: Typical acoustic signature identified due to the Power Take Off of *Lifesaver*. The STFT plot (31.25 Hz frequency bandwidth, 50% overlap, flat shading) shows variations in frequencies with time, and the colour coding details the relative magnitude of the power spectrum.

5. Discussion

The inability to distinguish WEC sound levels from background noise – and hence non-operational and operational modes- has been noted by a number of other studies [19,45]. The 1/7th scale *SeaRay* WEC was unable to estimate the source level of the device due to local shipping [46]. This could be subject to change when arrays of devices are deployed, as the noise from multiple devices in an array would combine, as discussed by Tougaard in [45].

Both methods of analysis in this paper were able to identify tonal elements to the WEC signal. In Figure 3, the difference between operational and non-operational median PSD show contributions from frequencies 30 – 100 Hz up to 1 dB re 1 μPa^2 Hz^{-1}. However when considering just 30 minutes of recordings, Figure 4 captures individual tonal elements within the same frequency range contributing up to 90 dB. This is believed to be associated with the WEC generator. This is not the first case of relatively low frequency noise elements being detected from WEC engineering components [19]. Tougaard [45] reported a 150 Hz tonal noise at 121-125 dB during the start and stop of the converter caused by the hydraulic pump of *Wavestar* WEC, although data was collected for the short time period of one day. In case of the *SeaRay* WEC increased spectral levels below 1 kHz were noted, that are consistent with the WEC torque and shaft speed in the fore generator [46].

Time-frequency analysis revealed AE signatures of the active PTO system up to 90 dB at 200 m in the frequency range 100 Hz – 1 kHz that could be related to the fine scale dynamics of the PTO system and sea state. This gives a direct link into the engineering health of the device through its acoustics. In half of the studies of WECs, a link is drawn between the acoustics produced and converter operation (e.g. [47–49]). Lepper and Robinson found a number of "events" related to the acoustic emissions of the Pelamis device (rattles, bangs, clanking etc.) but did not draw any correlation to the mechanics of the device itself [47]. In retrospect it was possible to link the acoustics detected with the incorrect assembly of a WEC as part of the Lysekil project [48]. Unfortunately, the received level for these impulsive signals cannot be confirmed due to the sensors (located 20-m from the device) being overloaded. The authors did not connect the detected acoustic emission with the possibility of condition monitoring. The underwater acoustic emission of tidal devices has also been found to provide crucial information in retrospect. *Verdant Power* deployed 6 tidal turbines that when recorded were generating more noise than expected, believed to be related to the blades on one of the turbines being broken, and another failing [49].

No studies regarding the operational noise of WECs have analysed the data in view of engineering features towards exploring AE as a condition monitoring technique. This application was briefly mentioned in a very small number of reports as a future development possibility [19,50] and has been recently trialled for a tidal energy deployment [51].

AE offers a number of advantages over other methods of condition based monitoring that could theoretically be developed for the underwater environment to complement existing techniques. Firstly, sound does not attenuate as rapidly in water as it does in air. Acoustic signals can be detected at a substantial distance from a device as demonstrated through results presented in section 4.2, where acoustic equipment was located 200 m from the device of interest. This could allow multiple devices or components to be monitored simultaneously.

Another advantage is that this monitoring technique does not necessarily require the development of new equipment, as specialist hydrophones such as the AMAR used in the case study are commercially available. However, it is noted that for continual and real time monitoring, collection and re-deployment of sensors would not be suitable; real time data transfer would be preferred.

The development of such condition monitoring will also be of benefit to environmental impact assessments, allowing the identification of device components that are particularly noisy or faults that produce elevated noise levels than typical operations.

However, there are currently a number of limitations to this new method of condition monitoring for MRE devices to be considered. The novelty of this method means that it is still being developed and tested. The identification of appropriate components to monitor needs to occur through specific component testing, and the feasibility of this system in practise and in the field needs to be explored. Yet, the results presented in this paper give initial confidence that this method is feasible. Another practical challenge is the amount of acoustic data recorded, meaning that efficient data acquisition, signal processing techniques and the storage/transmission of data will be vital to the success of a remote and continual monitoring system.

In this study, another limitation was the use of only one hydrophone. The use of multiple hydrophones would have allowed the identification of the direction (bearing) of the sound source locations through time-of-arrival triangulation. This would be of particular interest when considering device arrays, to detect a device among many. One concern regarding commercially available airborne AE systems is the "false alarm" rate [52]. The use of multiple sensors would allow for a more accurate decision as to the reality of a signal by comparing multiple recording of the same acoustic signature.

This method of condition monitoring is not confined to just the *Lifesaver* WEC, as shown by the numerous examples of acoustic signatures discovered in other studies (e.g. [19,45,48]). Acoustic signatures will be dependent upon device design and components. There is a large variety of device designs in the industry that include different moving elements, mooring and anchoring systems and locations within the water column. However, this can be overcome with bespoke signal processing looking for abnormalities in a received signal, and through individual testing for the more commonly used components. Hence, this could also be transferable to tidal stream devices and other offshore developments.

6. Conclusion

In conclusion, systematic analyses of these long-term acoustic measurements near the Lifesaver WEC in Falmouth Bay show that:

- The ambient levels exhibited negligible average difference between operational and non-operational periods, although there were regular differences in the 30-100 Hz range.
- Detailed time-frequency analyses show the AE signature of the active PTO system during WEC operation (0.5-second 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. Tonal components at 30, 60, 80 and 100 Hz, reaching 90 dB re 1 µPa^2 Hz^{-1} were also attributed to the device generator.
- Although most AE measurements to date have focused on sensors close to the devices/components of interest, in underwater environments, it is possible to detect AE signatures 200 m away from this WEC at its deployment site.

In order to improve the viability of MRE the cost of operation and maintenance activities must be reduced. Condition based maintenance has proved successful in other renewable energy sectors and the underwater environment in which MRE devices reside provides an opportunity to develop underwater Acoustic Emission as a remote condition monitoring tool. Acoustic data from a 2-year deployment of the Fred. Olsen *Lifesaver* WEC at *FaBTest* in Falmouth Bay (UK) has been processed using detailed time series and frequency analysis. While the contribution of the WEC was found to be insignificant overall in an active port, results show bursts of sound, 0.5 s in duration and up to 90 dB re 1 µPa^2 Hz^{-1}, that were related to the PTO of the device. It was possible to connect this acoustic signature to both the system dynamics and the changing environmental conditions. This is the first step towards the implementation of this novel method of underwater AE condition monitoring for MRE devices and components. In order to fully analyse the two year data set, we are currently developing automated data processing algorithms which are based on the acoustic signature profiles presented. As such, a complete statistical analysis and evaluation of the full data set will be the subject of a subsequent paper.

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Appendix A

Supplementary data for acoustic signatures.

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