Acoustic Emission Health Monitoring of Marine Renewables

Illustration with a Wave Energy Converter in Falmouth Bay (UK)

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***Abstract*—Marine renewable energy (MRE) is an emerging technology and at present there are an increasing number of MRE prototypes and full-scale devices deployed. The future commercialization in the near future may contribute to the mitigation of carbon emissions and diversify the renewable electricity generation portfolio. Because of the high costs of marine intervention, it is important to establish reliable, remote monitoring techniques. The underwater sound around MRE devices is often monitored for environmental impact assessments. This approach can also be potentially utilized to monitor the engineering health of MRE devices. This is the objective of the project ÆMORE (*Acoustic Emission technology for environmental and engineering health Monitoring of Offshore Renewable Energy*), jointly conducted by the Universities of Exeter and Bath, with J+S Ltd.**

Acoustic Emission (AE) monitoring is already used for Structural Health Monitoring (SHM) of land-based structures and devices such as wind turbines. AE allows faults and defects to be detected early in a device's lifetime, providing more time to plan and implement necessary maintenance and repair procedures to avoid catastrophic failure. This is highly desirable for MRE structures, which operate in energetic seas with tight weather access windows.

This paper explores the remit for AE monitoring to SHM and maintenance planning for MRE devices and demonstrates that this novel application is principally feasible. A brief review of the state of the art of AE for *land-based* systems aids to illustrate how its techniques can be applied to *underwater* environments and MRE components. This literature review will inform a classification system that relates likely failure modes to their expected acoustic emissions. The results from previous underwater environmental studies are used to evaluate their potential for SHM of MRE structures. AE environmental data collected during the operation of the Fred Olsen Lifesaver wave energy converter at the Falmouth Bay Test site (FaBTest, SW UK) is used to demonstrate this novel application. The case study provides proof that this concept is valid for underwater SHM of marine renewable structures.

Keywords*— Condition Monitoring; Health Monitoring; Marine Renewable Energy; Wave Energy Converter; Acoustic Emission; Underwater Acoustics; Ambient Noise

I. INTRODUCTION

In 2010, the energy supply sector produced 35% of the total anthropogenic greenhouse gas (GHG) emission [1], emphasizing the impact that this sector has upon annual emissions. Renewable energy technologies have significant potential to mitigate these emissions as acknowledged by UK [2] and international policy [3]. This includes established technologies such as wind and solar power as well as emerging ones such as marine renewable energy (MRE). It is estimated that up to 20% of the UK's current electricity supply could be met by wave and tidal energy alone [4]. This has led to intensive research and development efforts around Wave Energy Converters (WEC) and Tidal Stream Devices (TSD). WEC will be the focus of this paper but the principles of this work could also be applied to TSD.

WEC development has not yet converged to a uniform device design, unlike the wind energy sector (which led to the preference for 3-blade turbines). Instead, a number of devices are being studied simultaneously; they can be split into 9 categories as per the classification by EMEC (European Marine Energy Centre) [5]. A number of developers have tested large-scale prototype devices suggesting that commercialization could occur in the near future. However, there are concerns regarding the cost of Operation and Maintenance (O&M) of WEC and recent setbacks within the industry which will hinder the prospects of commercialization.

The high O&M costs of WECs result from the high costs associated with marine intervention in challenging waters and using specific vessels with limited availabilities. WECs operate in energetic sea states by design but this poses two problems. Firstly, harsh conditions at sea could cause damage or failure of devices, as already experienced by a number of prototypes [6]. Across its lifetime, a WEC must be robust, reliable and maintained effectively or face expensive unexpected maintenance costs and downtime. Secondly, weather windows for access to WECs for O&M activities do not always coincide with access needs. During large sea states, when damage is more likely to occur and hence when access is most needed, appropriate weather windows are short and far between [7]. This could result in further damage and longer periods of downtime, further impacting the O&M costs. Further down the line, large O&M costs impact upon the cost of energy, which, if not competitive with other renewable energy technologies, will impede the development of the MRE industry.

In this paper, we propose using underwater Acoustic Emission as a remote condition monitoring technique to reduce the O&M costs of WECs and increase their reliability, hence improving their viability as an emerging renewable energy technology. The paper presents the progress made through project ÆMORE, *Acoustic **E**mission technology for environmental and engineering health **M**onitoring of **O**ffshore **R**enewable **E**nergy*, initiated in October 2014. The project aims to assess the feasibility of combining the established techniques of remote condition monitoring in air with the environmental impact assessments already made using underwater acoustics. This should lead the way for the development of a novel method of remotely monitoring the engineering health of marine devices.

Section II gives a contextual overview of the wind energy sector's methods of O&M, including present maintenance strategies and acoustic emission condition monitoring. Section III introduces the proposed idea of monitoring MRE devices with underwater acoustics. Section IV discusses the environmental monitoring of MRE devices with underwater acoustics. Section V presents a case study of acoustic emissions by the Fred Olsen *Lifesaver* WEC. These different strands are discussed in Section VI, whilst Section VII presents the main conclusions and areas to be explored in further work.

II. THE WIND ENERGY SECTOR

Over the last 20 years, the wind energy sector has grown into the largest widely used renewable energy technologies. Designs have started to move towards larger offshore turbines, which face similar problems to marine renewables regarding the high cost and difficulty of marine intervention. MRE can therefore learn from this sector, regarding how it will overcome these difficulties, using tried and tested maintenance strategies and adapting condition monitoring techniques.

A. Maintenance Strategies

The wind energy sector can be considered as an established industry, presently facing high O&M costs for offshore wind turbines. This is mainly due to the large downtime associated with failures. Data from 750 onshore wind turbines in Sweden during the period 1989-2005 was analyzed to show that 75% of annual downtime was caused by only 15% of failures [8]. Studies have shown that these failures usually originate within subsystems centered on the drive train, including the main shaft and bearings, gearbox, rotor brake, blades and generator [9]. Multiple strategies have been adopted for maintenance on wind turbines, including reactive maintenance (operating until a failure occurs), preventative maintenance (periodic repair and replacement of parts regardless of condition) and more recently condition-based maintenance (CBM) [10].

CBM involves continually monitoring and inspecting system parts to predict the onset of a failure, and determine the necessary maintenance before the failure occurs. It has been shown to improve operational safety, reduce the number and severity of system failures and minimize O&M costs [10]. For an offshore wind turbine, O&M costs are estimated to be 20-25% of the total income [9]. CBM is achieved with condition monitoring techniques that use sensors and signal processing to detect indications of component condition and onsets of degradation. Examples include vibration analysis, strain measurements, oil analysis and acoustic emission.

B. Acoustic Emission Monitoring

AE is the sound produced by friction or the release of potential energy within a material. Within the context of CBM, acoustic emission is defined as transient elastic waves generated by a sudden release of energy caused by damage to a material, and occurs within the high frequency ranges of 100 kHz to 1 MHz [11]. Lower frequencies are generally investigated with vibration analysis. AE can produce 2 types of signals: impulsive (distinct acoustic signals, separate in time) or continuous signal(s) (impulsive waveforms are not individually distinguishable). Typical signal processing techniques used for diagnosis are signal amplitude, rms, energy, kurtosis, crest factor, counts, events, wavelet analysis and Fast Fourier Transforms (FFT), depending upon the type of signal.

Although AE was originally developed for non-destructive testing of static structures, it has been adapted to monitor the health of rotating machines, including bearings, gearboxes and pumps [11]. In rotating machinery, AE could be caused by cyclic fatigue, friction, material loss, cavitation etc. Commercially available AE sensors are usually piezoelectric transducers, placed directly on or close to the part to be monitored, as currently used within the wind energy sector.

AE has had a number of successes over the years. It can detect defects earlier than vibration analysis within bearings e.g. [12] and gearboxes e.g. [13], using a variety of signal processing techniques. Earlier detection gives more time to prepare for maintenance and/or failure. For the operation of pump machinery, it is accepted that best efficiency occurs with minimal flow turbulence in the system, i.e. minimum AE activity [14]. For composite materials such as in moorings, there are direct correlations between AE and breaks of fibers [15] or steel wire cables [16]. These studies and others (detailed in [11]) show the potential of this technology for a wide variety of components.

III. UNDERWATER ACOUSTIC EMISSION MONITORING OF MARINE RENEWABLES

It is important for MRE device developers to consider O&M strategies suitable for long term deployment of grid connected devices, not just for prototype testing. Project ÆMORE aims to provide a solution by taking AE technology already used by other energy sectors (Section 2.2) and adapting it to underwater devices.

AE offers a number of advantages. In an underwater environment there is often a large amount of low frequency ambient noise (<10 kHz), especially with local shipping which can be intermittent. CBM AE primarily focuses on the higher frequencies as a way of monitoring a system where there would be less interference from ambient noise. Underwater there is also a possibility of monitoring lower frequencies (<100 kHz) compared to in air. The frequency ranges of interest will become clearer once specific components have been tested but for the remainder of this paper, we conservatively assume that all frequencies in the range 1 Hz – 1 MHz can provide useful information.

Another advantage is that sound does not attenuate as quickly in water as in air (although underwater higher frequencies do attenuate faster than low frequencies). Sensors can be placed away from a WEC, where they can monitor multiple parts of a system at once. The use of water as a “connecting medium” in [17] was very successful detecting wire breaks with no reduction in signal amplitude. Some information (e.g. shear waves, evidently not transmitted through water) was lost, or reduced to specific components. AE associated to wire fracturing was also investigated in air [15], which showed a direct correlation between wire breaks and AE counts. Similar results were obtained for fibers, also in air [18]. Impulsive AE would be expected to follow the same principles underwater.

Experiments with other components in air give indications of what to expect underwater. Rolling element bearings can produce both impulsive and continuous emissions across a wide frequency range (up to 2 MHz), and it can be related to the geometry and speed of the bearing. Signal processing techniques such as ringdown counts, energy, rms and peak amplitude have all shown events to increase with the size of different types of defects [19]–[21]. In [22], faults were detectable 0.3 m from the bearing, whereas within all other investigations, sensors were placed onto or very close to bearings.

Evidence of degradation within gearboxes produces similar acoustic results. High frequency (up to 1 MHz) impulsive and continuous-type components would therefore be expected. Amplitude, rms and ringdown counts all increased with defect size in e.g., [13], [23], [24] and it was also found that rms increased with misalignment of gears [27]. In these studies, sensors were placed upon gears or on the gearbox.

Although pumps are not always found in WEC systems, there have been investigations in air and in water into the detection of incipient cavitation. Cavitation in air corresponds to a continuous broadband spectrum (20 Hz – 20 kHz) [25], and incipient cavitation produced an increase in rms and peak amplitude [14], [25]. Similar results underwater were found whilst studying a similar frequency range (0 – 100 kHz) [25].

Table I summarizes these results and provide a quality matrix of acoustic properties, faults and expected frequency ranges, emission types and general findings of studies in air (unless otherwise stated). These are useful when considering similar faults underwater. It is important to note that frequency analyses were conducted in some references e.g. [17], [24], but as it is not directly transferable to an underwater situation, it is not included in Table I.

IV. UNDERWATER ACOUSTIC MONITORING

Underwater acoustics is the method of choice in assessing the environmental impact of the sound radiated by WECs and other underwater operations. Generally these studies inspect Sound Pressure Levels (SPL) and variations, e.g. rms, over extended periods of time to investigate the impact that the sound pressure level (SPL) created by the WEC could have upon the behavior and health of marine wildlife [28]. These generic measurements, done for environmental purposes, already revealed a number of engineering events and faults.

Tonal elements of WECs have been commented on in a number of studies. For the *Wavestar* WEC, the tonal noise of the hydraulic pump during start-up and shut-down was

TABLE I. *QUALITY MATRIX OF ACOUSTIC EMISSIONS OF COMPONENTS RELEVANT TO UNDERWATER AE TECHNIQUES.*

Mechanical Part	Fault details	Frequency Range	Emission	General findings	References
Rolling Element Bearing (Ball bearing and cylindrical bearing)	Natural and seeded defects located on inner race, outer race, roller and ball of bearings	In air 100 kHz – 2 MHz	Impulsive and continuous components	Increase in ringdown counts and energy with defect size. rms and peak amplitude increased with defect size for rough, point and line defects. Ability to detect faults 0.3 m from bearing.	[19], [20] [13], [21] [22]
Gearbox	Pitting and scuffing of gear tooth	In air 100 kHz – 1 MHz	Impulsive and continuous components	Increase in rms with defect size and due to misalignment. Increase in (wideband) amplitude and Ringdown counts with defect size.	[13], [23] [23], [24]
Pump	Incipient and developed cavitation	In air 5 Hz – 20 kHz	Continuous	Noise minimum at best-efficiency point, due to minimal flow turbulence. Cavitation produces broadband acoustic spectrum. Increase in rms and peak amplitude when cavitation onset.	[14], [25] [25] [14], [25]
		Underwater 0 kHz – 100 kHz	Continuous	Frequencies <8 kHz contained mechanical noise and >40 kHz had greater resolution.	[26]
Rope	Fibre and wire rope fractures and breaks	In air 0 kHz – 600 kHz	Impulsive	1-to-1 correlation between AE events and broken fibres/wires.	[15], [18]
	Wire rope breaks	In air *through* water 0 Hz – 100 kHz	Impulsive	Wire breaks detected from 100 mm away. No information at frequencies <25 kHz due to non-propagation of shear waves.	[17] [17]

discernible [29]. The *SeaRay* WEC induced increases in spectral levels consistent with the torque and shaft speeds in the fore generator [30]. These cases provide evidence that WEC engineering processes are detectable, even when data collection efforts are not specifically geared toward their detection.

Impulsive signals have also been recorded from MRE devices. Impulses with an effective peak-peak source level estimated as 154 – 173 dB re 1 µPa were recorded from the *Scotrenewables Tidal Power Ltd* WEC and attributed to the anchor block and clump weight [29]. The *Pelamis* WEC was associated to a “clanking” sound 333 m from the device, with no discussion as to its possible source [32]. This particular signal lasted ca. 1 s, within a frequency range of 0 – 6 kHz, strongest around 1 kHz. Two other studies revealed unexpected acoustic signals, later attributed to device faults. *Verdant* tidal turbines generated “more noise than was expected” [29], and it was later found that a blade on one of the six turbines was broken and another was subject to an incipient failure. Measurements of two point absorber WECs at Lysekil [33] reported a number of 1-s high-amplitude impulses that saturated the recorder (up to 20 kHz). These impulses were found to be due to impacts on the end stop within the WECs. At the times of recording, the significant wave height was 0.5 m, below the 2-m peak-to-peak wave height expected to fully activate the end stop. It was later found that the device closest to the hydrophone (20 m away) was incorrectly assembled and causing these acoustic emissions.


Fig. 1. Bolt-2 *Lifesaver* WEC at the FaBTest site. [31]

V. CASE STUDY – *LIFESAVER* AT FABTEST

In 2012, Fred Olsen deployed and trialed their Electro-mechanical WEC at the Falmouth Bay Test Site (FaBTest) in Cornwall, UK [31]. The *Lifesaver* WEC is a 16-m wide, ring-shaped device with three Power Take Off (PTO) systems installed as shown in Fig. 1 [31]. *Lifesaver* is a floating point-absorber type WEC, producing power from the heaving motion, independent of wave direction [34].

To study the effect of *Lifesaver*’s noise on marine life, a hydrophone, recording and storage system (AMAR from Jasco Applied Sciences Ltd.) was positioned 200 m from the WEC. The AMAR was recording for half an hour every hour, over a broad band of frequencies (10 Hz to 32 kHz). The data was collected for two years, with regular recovery and downloading of measurements resulting in seven deployments [35]. The AMAR recordings allowed the long term monitoring of the underwater sound levels at sea during operational and

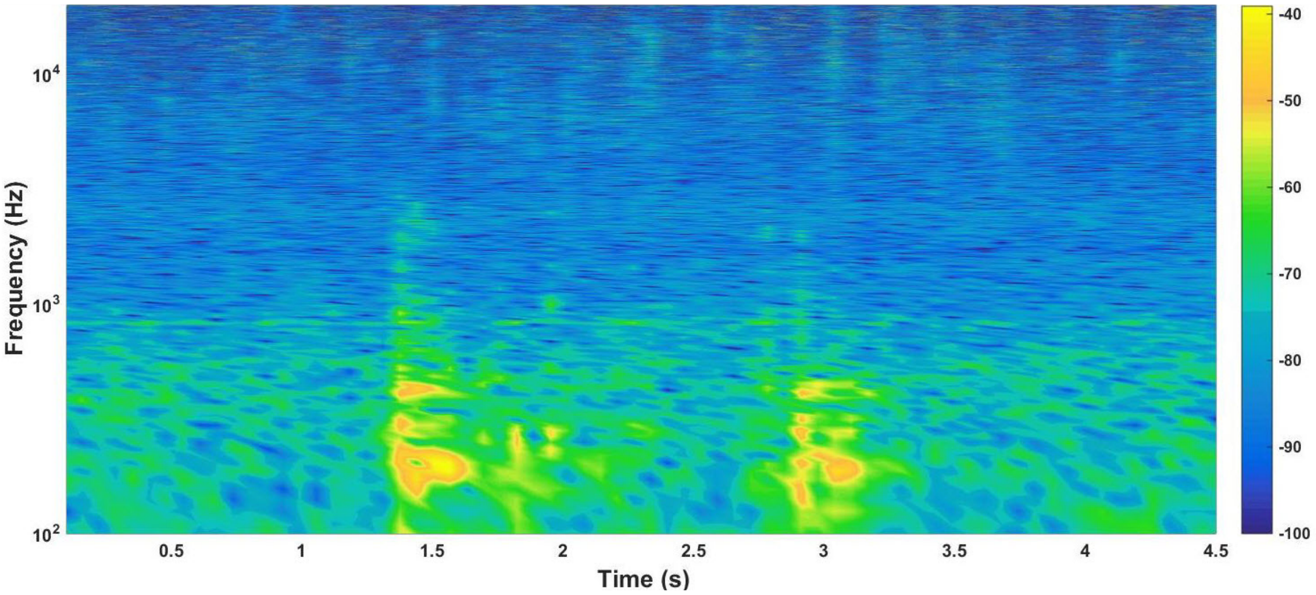

Fig. 2. Typical acoustic signature identified due to the Power Take Off of *Lifesaver.* The STFT plot shows variations in frequencies with time, and the color coding details the relative magnitude of the power spectrum (-100 dB to -40 dB).

non-operational modes of the PTO devices on *Lifesaver*.

In the present study, the acoustic data collected for environmental purposes has been re-analyzed to check the feasibility of conditional health monitoring of MRE devices. The main aim for this analysis was to identify acoustic events and relate them with actual activity in the sea. More specifically, this aimed to identify acoustic signatures caused by the wave energy device. Data was analyzed with Short Time Fourier Transform (STFT). Power spectral densities was visualized (e.g. Fig. 2) and related to specific events.

The *Lifesaver* PTO system is realized as a winch and rope system, schematized in Fig. 3. The generator can only produce power during upwards motion and has to operate in motoring mode during downwards motion to wind the rope back to the drum. The rope in the PTO is realized as a belt drive system. When the sea state is high, i.e. large wave heights, the PTO winch system undergoes rapid movement. Sjolte describes in [31] that in higher production states, the winch and the floater system occasionally showed rapid vibrations. This is believed to be caused by the dynamic response of the primary mooring, which results in an unforeseen aggregate system response.

This vibration was detected by the AMAR. Fig. 2 shows the acoustic signature of vibration and resonance in the primary mooring system. This is further supported by the analysis of wave-buoy data at FaBTest. We find that the number of PTO acoustic signatures is directly proportional to the sea state. As described by Sjolte [31], high sea states produced more vibration and tension creating more acoustic signatures observed by the hydrophone.

This signature was detected despite relatively high levels of background noise from the area. Falmouth Harbour is a busy commercial port with more than 1,000 ship arrivals reported in 2012 and it also supports many recreational boat activities [35]. Also, the AMAR was placed at a distance of 200 m from the device, causing a considerable amount of frequency-dependent attenuation to the sound.

VI. DISCUSSION

Although there are a number of remote condition monitoring techniques that would theoretically be transferrable to an underwater environment, AE provides a number of advantages. Firstly, sound travels further distances under water than in air, and hence the distance at which sensors should be placed to monitor a single device or array of devices is greatly increased. This has been shown earlier, e.g. [17], and further demonstrated with this 2-year series of measurements. Secondly, commercially available hydrophones are fully capable of detecting the signals and properties described in Table I. Table II, outlines for example the key properties of 3 suitable hydrophones made by our industrial partner J+S Ltd. This includes a range of frequencies (up to 125 kHz), suitable operational depths of >100 m, and the provision of a line array will be used for triangulation of acoustic signals. Finally, underwater acoustic is already being used for environmental assessment of MRE devices. It thus makes sense to combine these two techniques to provide WEC developers with one sensor that can meet the needs of both environmental assessment and engineering health monitoring.

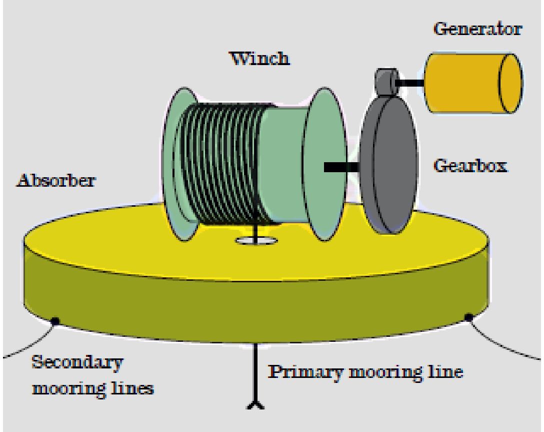

Fig. 3. Schematic for Power Take Off systems installed on WECs such as the *Lifesaver* [31]

However, there are a number of limitations that need to be overcome in order to make this technique viable. Mainly, this technique is still very much in a development and testing stage, in terms of both identifying which components this technique is suitable for, and what signal processing steps are required. Another challenge is the sheer volume of data (e.g. 2-year broadband monitoring of the *Lifesaver* WEC, detecting and identifying AE processes lasting from less than a second to minutes or longer), data acquisition, signal conditioning and processing will need tailoring carefully, in particular to address monitoring of remote locations where regular recoveries to download the data at regular intervals are not possible.

Environmental assessments of MRE devices have been able to detect engineering events as shown in Table I. However the authors of these studies have only commented on the events that they have found, and not proceeded to investigate further how underwater acoustics can be used to remotely monitor the engineering health of MRE devices. Very few (e.g. [28]) have mentioned that characteristic acoustic signatures of faults and failures of mechanical parts offer "the potential for monitoring the structural health of [an] energy converter, and so acoustic sensors could provide a

TABLE II. J+S LTD. HYDROPHONES AND THEIR PROPERTIES

Hydrophone	**Resonant Freq. (kHz)**	**Flat band (kHz)**	**Received voltage sensitivity (dB re 1V/µPa)**	**Operational Depth (m)**
Ball hydrophone JS-B100-C4DS-PA	100	0.04-60	-168	>3000
Ball hydrophone JS-B300-C4DS	300	0.1-125	-207	>4000
Line array hydrophone JS-LPA-32	-	0.05-32	-167	>30 >100[a]

[a]deep variant

secondary purpose as a diagnostic tool."

This case study of the *Lifesaver* WEC, in which the acoustic signature of the PTO was regularly and reliably observed, provides strong evidence that acoustic health monitoring can assist in continuously monitoring the tension and vibration in the primary mooring system and provides the first step to proving the feasibility of this novel method to monitor the engineering health of submerged MRE devices.

Its main asset is the potential for detection of incipient failures, not just the detection of the failures themselves. When the acoustic emission from a failure is detected, it is too late to proceed with any intervention, as the failure has already occurred. The ability to detect incipient failures, for example through signs of degradation and faults, would be a useful diagnostic tool to monitor the state of the device. This would allow its maintenance schedule to be revised and intervention arrangement made if necessary hence reducing the need for unnecessary interventions which are time consuming and costly. Alternative arrangements for its operation in the meantime could also be achieved (e.g. use in lower sea states).

VII. CONCLUSION AND FURTHER WORK

This paper presents a novel method of remote condition monitoring for MRE devices. Relevant literature from AE in air and environmental assessments in water has been reassessed for this innovative purpose. This has led to a quality matrix of possible AE signatures for engineering components relevant to MRE devices including gears, bearings and rope. It is expected that a selection of impulsive and continuous emissions with a broad range of frequencies can be detected, depending upon the mechanical part investigated. Engineering events noted by various authors have also been collated from environmental assessment literature. The *Lifesaver* case study outlined provides strong evidence to suggest that this method of remote monitoring could prove successful.

Current and future work makes use of the University of Exeter's Dynamic Marine Component (DMaC) test facility [6] to investigate acoustic signatures specific to individual components. Subsequent modelling will be further tested using the University of Bath's test tanks and open-water sites.

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