Acoustic Characteristics of the Lifesaver Wave Energy Converter

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***Abstract*— The Fred. Olsen Lifesaver, a point-absorber wave energy converter, was deployed at the US Navy Wave Energy Test Site in Kaneohe, HI (USA) from March 2016 to April 2017. A combination of free-drifting and stationary measurements were used to characterize its acoustic signature over a range of sea states. Comparisons are made between co-spatial and co-temporal observations that investigate temporal trends and identify sound originating from the test area. Initial free-drifting surveys suggested limited sound originating from the Lifesaver, but relatively high-amplitude, episodic sound originating from the mooring system. Because these observations were contaminated with flow-noise and self-noise, a refinement to compliantly couple the drifting hydrophone to its surface expression was implemented, providing good agreement with stationary observations. During a subsequent survey, sound from the power take-off could be identified, as well as a damaged bearing producing a characteristic warble. Such observations reinforce the ability of acoustic monitoring to provide condition health monitoring for marine energy systems. The episodic nature of sound around the Lifesaver motivates future classification algorithm development to discriminate between sound produced by the wave energy converter and sound produced by the other sources (e.g., moorings, marine mammals).**

***Keywords*— wave energy converter, acoustics, underwater sound, Wave Energy Test Site, Fred. Olsen Lifesaver**

I. INTRODUCTION

Wave energy has the potential to materially contribute to the global supply of renewable energy, but only through large-scale generation. As a consequence of their operation, wave energy converters (WECs) produce sound and, with widespread deployment could alter soundscapes for marine animals [1]. Analogously, it is desirable to minimize the acoustic emissions of smaller WECs in security and defence applications, such as undersea tactical networks or charging stations for autonomous underwater vehicles.

As a consequence of the multitude of WEC designs and the difficulty of obtaining acoustic measurements in high-energy wave environments, acoustic characterization has been limited. Most relevantly, Walsh et al. [2] characterized the Fred. Olsen Lifesaver during a two-year trial off Cornwall, UK. In this study a stationary hydrophone was deployed at a range of 200 m. Acoustic measurements showed tonal contributions from the power take-off (PTO) below 100 Hz, short (i.e., < 0.5 s) pulses between 100 Hz and 1 kHz associated with vibrations during high sea states, and intermittent tonal sound associated with the PTO generator centred around 100 Hz, 200 Hz and 300 Hz. Here, the characteristics of the same WEC are evaluated at a different site through a combination of stationary and free-drifting measurements.

II. BACKGROUND

A. Site Description

The US Navy Wave Energy Test Site (WETS) is located in Kaneohe, HI on the windward side of the island of Oahu and is within the restricted waters surrounding Marine Corps Base Hawai'i. WETS is a grid-connected wave energy test site with test berths located in 30 m, 60 m, and 80 m water depth, as shown in Fig. 1. The seabed in the area is predominantly bedrock, in some places overlaid with a thin layer of sand. At the 60 m and 80 m berths, there are permanent moorings for wave energy converters (WECs) under test. These consist of surface floats with links of chain descending to the seabed where a series of sinker weights augment chain inertia close to the drag embedment anchors. WECs are connected to these floats by tensioned hawser lines, forming a three-point

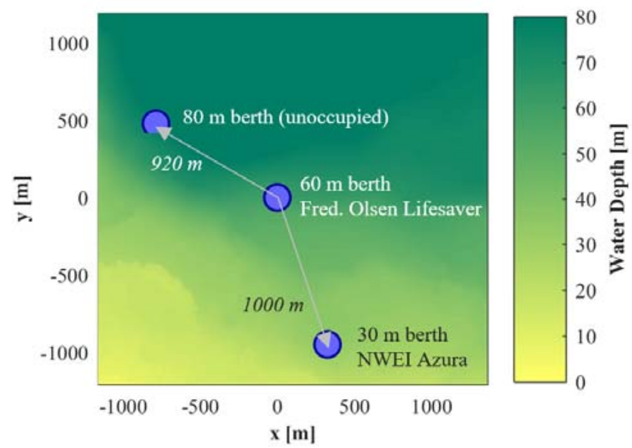

Fig. 1 WETS layout showing berth locations and occupancy, inter-berth distances, and bathymetry.

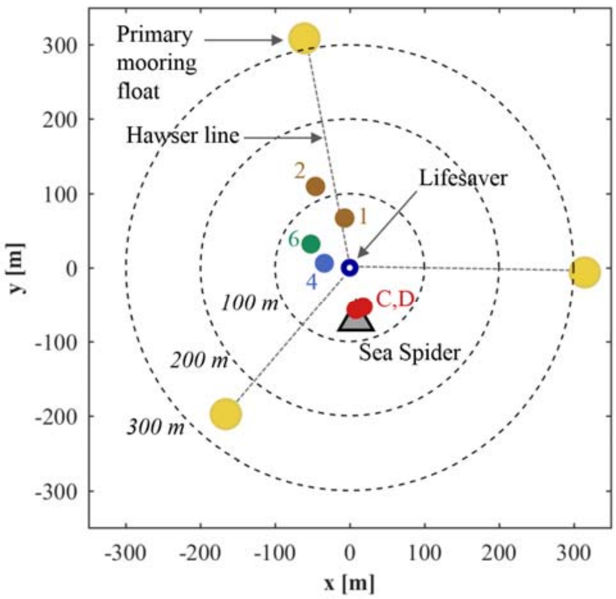

Fig. 2 60 m berth with Lifesaver, permanent moorings, and Sea Spider bottom platform (triangle). The locations of the free-drifting measurements summarized in Table I are noted by coloured circles, numbered by drift.

Fig. 3 Fred. Olsen Lifesaver wave energy converter at WETS.

catenary mooring. Fig. 2 shows the layout of the 60 m berth, which is the focus of this study.

A Waverider buoy (Datawell) is moored relatively close to the 60 m berth (100 – 300 m, depending on watch circle). Significant wave height (H_{m0}) and energy period (T_e) are publicly available in 30 minute intervals. WETS has a dominant energy period of ~7 s and can experience significant wave heights greater than 5 m [3].

B. Lifesaver Wave Energy Converter

The Fred. Olsen Lifesaver (Fig. 3) is a point-absorber consisting of a semi-submerged toroidal float (10 m inner diameter, 16 m outer diameter) with a relatively shallow draft (< 0.5 m). Power take-off consists of up to five topside rotary generators, each of which is connected to a winch line that extends from the toroid to a fixed mooring point. Wave-induced toroid motion extends and retracts these lines, yielding electrical power through a hydraulic generator. The Lifesaver was deployed at WETS in March 2016 at the 60 m berth and recovered in April 2017. As during prior testing off Cornwall, the Lifesaver was equipped with three power take-off units. Electrical power production and the number of operational power take-off units were provided by Fred. Olsen in 20-minute intervals. Between the UK and US deployments, Fred. Olsen modified the WEC control strategy to reduce the vibrational noise observed by Walsh et al. [2].

C. Ambient Noise

The soundscape at WETS is a combination of multiple natural and anthropogenic sources. At frequencies less than 1 kHz ambient noise is dominated by the sound from wind and waves [4]. At frequencies greater than 1 kHz, snapping shrimp often dominate [5]. Seasonally, humpback whales produce vocalizations that dominate in the range of 100 Hz to 1 kHz. Several anthropogenic sources are also present. The most persistent is chain noise from the unoccupied moorings at the 80 m, which produces a tone centred around 1.5 kHz. Military aircraft traffic periodically contributes short-duration tonal sound around 100 Hz [6] and vessel traffic periodically produces broadband, high-amplitude sound that can mask all other ambient noise. Throughout the measurements at the 60 m berth, a second WEC, the Northwest Energy Innovations Azura, was deployed at the 30 m berth. Acoustic characterization of that WEC indicates that the sound from its PTO is not detectable beyond a range of a few hundred meters [7] and is, therefore, unlikely to contaminate Lifesaver measurements.

III. Acoustic Measurements

Acoustic measurements were obtained by a combination of stationary and free-drifting instrumentation platforms.

A. Stationary Instrumentation

DSG-ST (Loggerhead Instruments) recording hydrophones were deployed on Sea Spider platforms (Oceanscience), with a piezoelectric element height of 0.9 m above the seabed (Fig. 4). Hydrophones were deployed in sets of three, with two configured for a sampling rate of 48 kHz on duty cycles (30 minutes of continuous recording every 90 minutes, with the start time staggered by 30 minutes). The third hydrophone was configured to sample at 96 kHz for 15 minutes every 90 minutes, co-temporal with one of the lower frequency units. The Sea Spider was deployed ~60 m from the WEC at the coordinates shown in Fig. 2 from December 6, 2016 through

Fig. 4 Sea Spider platform prepared for deployment

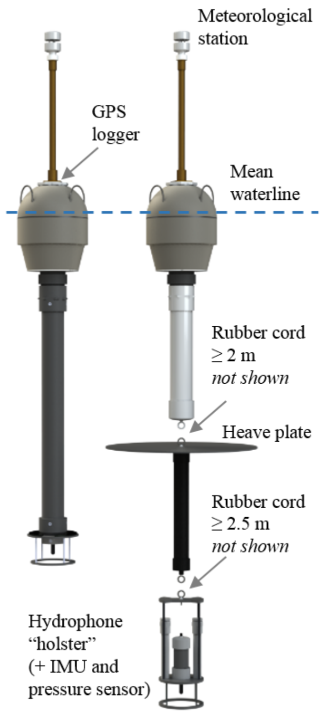

Fig. 5 DAISY variants: rigid hull (left), compliant coupling with heave plate (right)

March 8, 2017. In addition to the hydrophones, the Sea Spider was equipped with an inertial measurement unit (MAT-1, Lowell Instruments) to evaluate platform stability during long-period swell. For example, linear wave theory suggests that a 12 s wave with a height of 4 m would produce near-bed velocities of 1 m/s [8], which could mobilize the platform.

B. Free-drifting Instrumentation

Drifting measurements were collected by two variants of the Drifting Acoustic Instrumentation SYstem (DAISY), a custom package built around icListen HF (OceanSonics) recording hydrophones. The shorter duration of these measurements permitted sampling rates up to 512 kHz to characterize higher-frequency sound production than possible for the stationary hydrophones. In addition, free-drifting systems can be used to investigate horizontal and vertical variations in received levels. Each DAISY has a surface expression that includes a GPS tracker (QStarz BT-Q1000eX), inertial measurement unit (MAT-1), and meteorological station (Airmar WX-200) recording wind speed and air temperature.

Measurements were conducted in August 2016 using a version of the DAISY derived from the SWIFT drifter [9], in which the hydrophone is suspended to a depth of 1.2 m by a rigid connection to the surface expression (Fig. 5, left). The "rigid hull" DAISYs are generally wave followers. However, there was enough differential movement between the hydrophone and water to produce flow-noise (i.e., pseudo-sound) [4, 10] and self-noise (e.g., propagating sound from DAISY components) that can mask received levels at frequencies below ~400 Hz. To explore lower frequencies, modified DAISYs were developed with a compliant connection between the hydrophone and surface expression. This "compliant coupling" consisted of a length of rubber cord, a heave plate, and second length of rubber cord, which created a mass-spring-damper that isolated the hydrophone from the motion of the surface expression (Fig. 5, right). The cord length was varied to obtain measurements at a variety of depths and, in one case, a pair of hydrophones was deployed in-line as a simple vertical array. This is functionally similar to the suspension systems used in sonobuoys (e.g., [11]) and low-frequency ambient noise measurements (e.g., [12]).

DAISY surveys discussed in this paper are summarized in Table I, and drift locations in the vicinity of the Lifesaver indicated on Fig. 2. The sound velocity profile was sampled (Valeport MiniSVP) once per day during drifting surveys and were relatively uniform, rarely varying by more than 1 m/s over the upper 30 m of the water column..

C. Acoustic Processing

Acoustic data were processed in Matlab using a Fast Fourier Transform. Because the sampling rates varied between the drifting and stationary measurements, window intervals were varied to yield the same frequency and temporal resolution, 8 Hz and 0.064 s, respectively.

For drifting measurements, with a sample rate of 512 kHz, voltage data were windowed into intervals of 65,536 (2^{16}) points, overlapped by 50%, and tapered by a Hamming window. Frequency-specific hydrophone sensitivities were applied based on a laboratory calibration for $f < 1$ kHz (University of Victoria) and manufacturer-supplied calibration for higher frequencies. No *in-situ* calibration of the complete system (i.e., hydrophone and isolation system) was performed.

For stationary measurements, voltage data were windowed into intervals of 12,288 points, overlapped by 50%, and tapered by a Hamming window to yield the same frequency and temporal resolution as the drifting measurements. Frequency-specific sensitivities were developed using a pistonphone calibrator (GeoSpectrum M351) at frequencies below 250 Hz and were combined with manufacturer calibration data at higher frequencies. For both types of surveys, the pistonphone calibrator was used to verify hydrophone integrity during surveys. As for the drifting measurements, no *in-situ* calibration was performed on the complete system (i.e., hydrophone and tripod).

Acoustic data are presented primarily in pressure spectral density (PSD) in units of dB re 1μPa^2/Hz, either as spectrograms or periodograms. For spectrograms, the median PSD is removed to visually emphasize extrema. For periodograms, band-averaging is applied over an increasing number of frequencies (i.e., "progressively smoothed") to "declutter" the visualization of higher frequencies. Statistics for stationary data are quantified by band-limited levels in units of dB re 1μPa.

D. Free-drifting Analysis

Sounds in free-drifting measurements were manually classified by playing back recorded sounds overlaid on a spectrogram and voltage trace. For comparisons between co-temporal measurements (e.g., hydrophones at different locations), time series were shifted to align ambient noise events and compensate for direct path propagation time and asynchronous clock drift. Corrections were generally on the order of one second. To synchronize free-drifting and stationary measurement platforms, an acoustic source (OceanSonics icTalk HF) was used to transmit a repeated tone at 10 kHz.

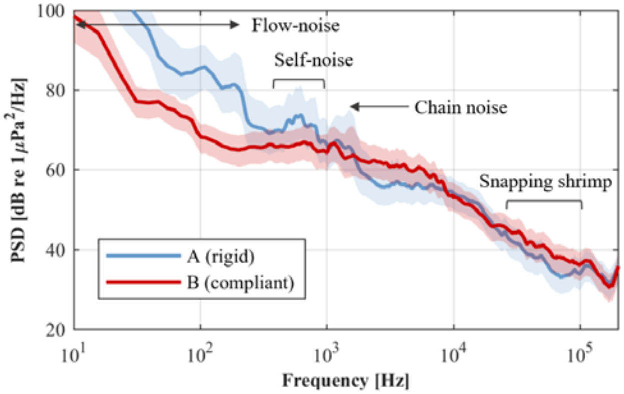

Fig. 6 Comparison of co-temporal spectra (60 s duration), annotated with specific features. Thick line shows median values, transparency denotes interquartile range.

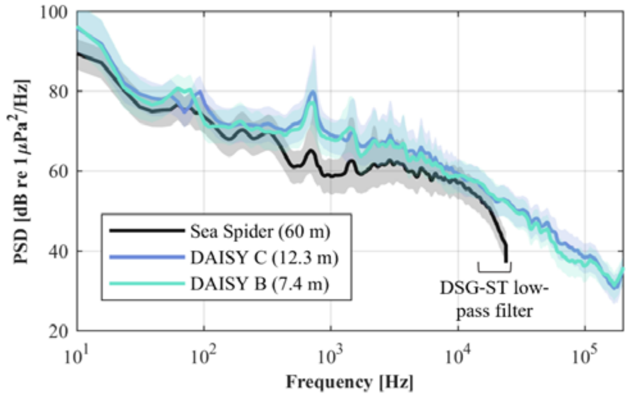

Fig. 7 Comparison of co-temporal and co-spatial Sea Spider and compliantly-coupled DAISY measurements. Spectral peaks are annotated in Fig. 14.

TABLE I
DRIFTING SURVEY SUMMARY (*R* DENOTES AN AMBIENT REFERENCE DRIFT)

		Lifesaver Proximity		**Lifesaver Status**		**Metocean Conditions**			**DAISY**	
Drift	**Date/Time (HST)**	Range [m]	θ [deg]	Power [kW]	PTOs	Wind [m/s]	H_{m0} [m]	T_e [s]	Hydrophone Depth [m]	Configuration
Platform Inter-comparison										
A	Dec 2, 2016	*80 m berth*				6±2	2.4	7.9	1.2	Rigid spar
B	08:38 AM								7.8	Compliant coupling
C	Jan 24, 2017	56	-71	1.8	2	6±1	2.2	8.3	7.4	Compliant coupling
D	8:16 AM	58	-82	1.8	2				12.3	Compliant coupling
August 2016										
1	Aug 19, 2016 10:01 AM	67	96	n/a	n/a	4±2	1.6	6.1	1.2	Rigid spar
2		120	114			n/a				
3*R*		570	15			5±1				
January 2017										
4	Jan 27, 2017	35	170	1.5	2	n/a	2.1	9.2	12.3*	Compliant coupling
5*R*	08:51 AM	1200	4			5±1				

*Estimated from other drifts (co-temporal depth data not recorded)

E. Stationary Analysis

PSD estimates were calculated over 30-second windows for all stationary platform data and binned by significant wave height and wave energy period with bin resolutions of 0.5 m and 1 s, respectively. PSD estimates were then sampled, at random, from the total data available at a given sea state. This distributed samples over the available data within a sea state bin to increase the temporal diversity of samples used in the analysis. However, a few sea states occurred infrequently during the deployment, such that all samples were drawn from temporal clusters. Each sample was manually reviewed and samples contaminated by boat noise or self-noise were excluded. Ten PSD samples were selected for each sea state bin for a total of 300 seconds of data. An ensemble average of PSD samples was then calculated in units of pressure squared per Hertz for each sea state bin. Finally, each PSD estimate was integrated into band-limited sound pressure levels. Broadband (0 - 20 kHz) sound pressure level (SPL) was calculated by integration of 30 second PSD estimates to produce overall deployment statistics.

IV. RESULTS

A. Platform Comparisons

A comparison of the compliantly coupled and rigid hull DAISY configurations is presented in Fig. 6. These measurements were made at the unoccupied 80 m berth and were co-temporal, but spatially separated by 30 m. In general, received levels are consistent between configurations above 1 kHz. Below this frequency, a self-noise band exists in the rigid hull data at several hundred Hz and flow-noise dominates below 100 Hz. The compliant coupling was effective at lowering the flow-noise and eliminating the self-noise peak. The somewhat higher received levels for the compliantly-coupled hydrophone from 1-10 kHz are most likely either a consequence of reduced shadowing from the more open design or variations in transmission loss with depth.

Fig. 7 shows a co-temporal and co-spatial (20 m tolerance) comparison between compliantly coupled DAISYs at two depths and a Sea Spider. At frequencies below ~400 Hz, the interquartile ranges for all three measurements overlap, which further emphasizes that the compliant couplings largely eliminate flow-noise. At higher frequencies (e.g., 790 Hz) where near-surface sources produce tonal sound, the Sea Spider received levels are, unsurprisingly, lower than for the DAISYs. Above 20 kHz the frequency response of the Loggerhead DSG-ST rolls off, indicating a maximum useful frequency of no more than 20 kHz for a sampling rate of 48 kHz. The source of the spectral peaks are discussed in Section IV.B and time-resolved depth variations are further discussed in Section IV.**Error! Reference source not found.**.

B. Sound Characteristics

The sounds recorded in the vicinity of the Lifesaver are an amalgam of discontinuous events – only some of which may be attributed to the WEC. These sounds also varied significantly between initial drifting surveys in August 2016 and subsequent stationary and drifting surveys.

Fig. 8 shows spectrograms, annotated with manual classifications, from August 2016. Multiple, episodic sounds are present in the recordings: a broadband metallic impulse, a metallic rattle (reminiscent of shaking an aerosol can), distant chain noise (originating from the 80 m berth), and periods of self-noise and flow-noise associated rigid spar motion. The periodograms for representative sequences are shown in Fig. 10 and provide further insight into the origin and nature of these events. Each periodogram includes observations from a pair of DAISYs (Drifts 1 and 2) in relatively close proximity to the Lifesaver and a co-temporal measurement of sound at a "reference" location ~600 m to the east (Drift 3)[1]. For frequencies where the three spectra are coincident, the sound is unlikely to originate from the Lifesaver site (i.e., no difference in received levels over significant range). The 10th percentile spectrum at the reference location (evaluated over the 30-s sequence) is included to provide context for the relative elevation of sound during episodic events. The metallic impulse (d) is broadband, clearly elevating received levels from 1 kHz to 200 kHz. The metallic rattle (c) is centred around 1 kHz and does not contribute substantially to propagating sound above 5 kHz. The chain noise (b) originating from the 80 m berth has a tonal peak around 1.5 kHz, with lower-amplitude tonal components up to 4 kHz. Finally, the self-noise event (a) is a composite of propagating sound from the WEC site (i.e., similar features between a few hundred Hz and a few kHz in the reference spectrum) and self-noise/flow-noise dominating below 250 Hz (i.e., substantial differences in received levels over short distances). This masking, which obscures the acoustic features observed by [2], motivated the development of compliantly coupled DAISYs, deployed in December 2016 and January 2017. Qualitative measures of sound are similar between these surveys and only results from January 2017 are presented. As shown in Fig. 9, a variety of sounds is present in recordings, including impulsive metallic noises, lower-amplitude metallic rattles, distant chain noise, warbles with a duration similar to a wave period (likely associated with a damaged PTO bearing noted during visual inspection), and a low-frequency sweep (likely associated with a normal PTO operating mode). Some of these have spectral similarities to the sounds observed in August. Periodograms for representative events are shown in Fig. 11. The sound attributed to the functioning PTO (a) is centred around 100 Hz and is only distinguishable in manual review when no other significant sound sources are present. However, elevated sound at this frequency is observed in other event spectra, suggesting persistence in line with expectations from [2]. This sound was also likely present in August, but masked by flow-noise and self-noise caused by rigid spar motion. The periodic pulses between 100 Hz and 1 kHz observed by [2] are absent in these measurements, suggesting that the modifications undertaken by Fred. Olsen to reduce vibration were successful. The sound from the damaged bearing (b) has a primary tone at 790 Hz with higher harmonics up to 4 kHz. The spectral similarities between the metallic impulse sound (d) in August and January suggest a similar mechanism. Inspection of the permanent moorings early in 2017 identified damage from repeated contact between the chains and sinker weights, such that the temporal evolution may be a consequence of accumulated damage to the permanent moorings. Similarly, the spectral similarities of the metallic rattles (c) may indicate a comparable evolution. These sounds are all clearly detectable at the reference site 1200 m away, albeit at reduced amplitude.

C. Temporal Statistics

The stationary platform (Sea Spider) was deployed for 93.2 days and produced 68.2 days of acoustic data. The median broadband SPL for the 30-s processing windows was approximately 114 dB re 1μPa and mean levels as high as 159 dB re 1μPa were infrequently observed for individual windows (Fig. 12).

Received levels exceeded the US regulatory threshold for auditory harassment of marine mammals (broadband level of 120 dB re 1μPa) for only 1% of the deployment. Further, these exceedance events are dominated by non-propagating flow-noise and sources unrelated to the Lifesaver (e.g., chain rattle and impulsive sound associated with abnormal performance of the permanent moorings). A rigorous estimate for the WEC source levels would require more extensive geoacoustical information and acoustic modelling, as well as a clear identification of sounds solely associated with the WEC to

[1] The choice of the reference location was *post-hoc* from available drifts. In August 2016, based on prior measurements around the other WEC at WETS [7], a standoff distance of 600 m was expected to be representative of ambient conditions. After analyzing those results, the standoff distance was increased to 1200 m in January 2017, which is still insufficient to entirely escape the acoustic influence of the Lifesaver and mooring. Stationary acoustic measurements in the absence of the WEC are ongoing, but a comparison to "baseline" values may be non-trivial given the variety of ambient and anthropogenic noise sources present [13].

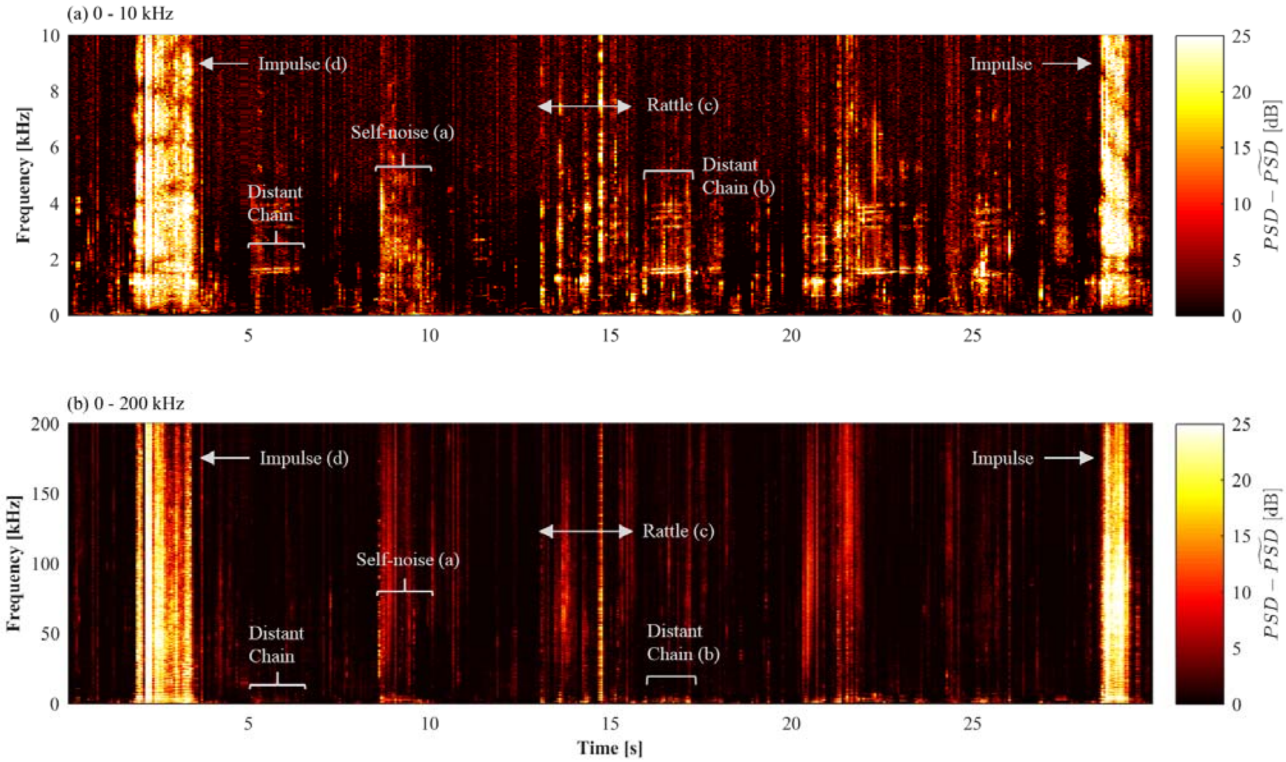

Fig. 8 Spectrograms from August 2016 (Drift 1). (a) Detail from 0 – 10 kHz. (b) Full frequency range from 0 – 200 kHz. Distance to WEC is ~70 m.

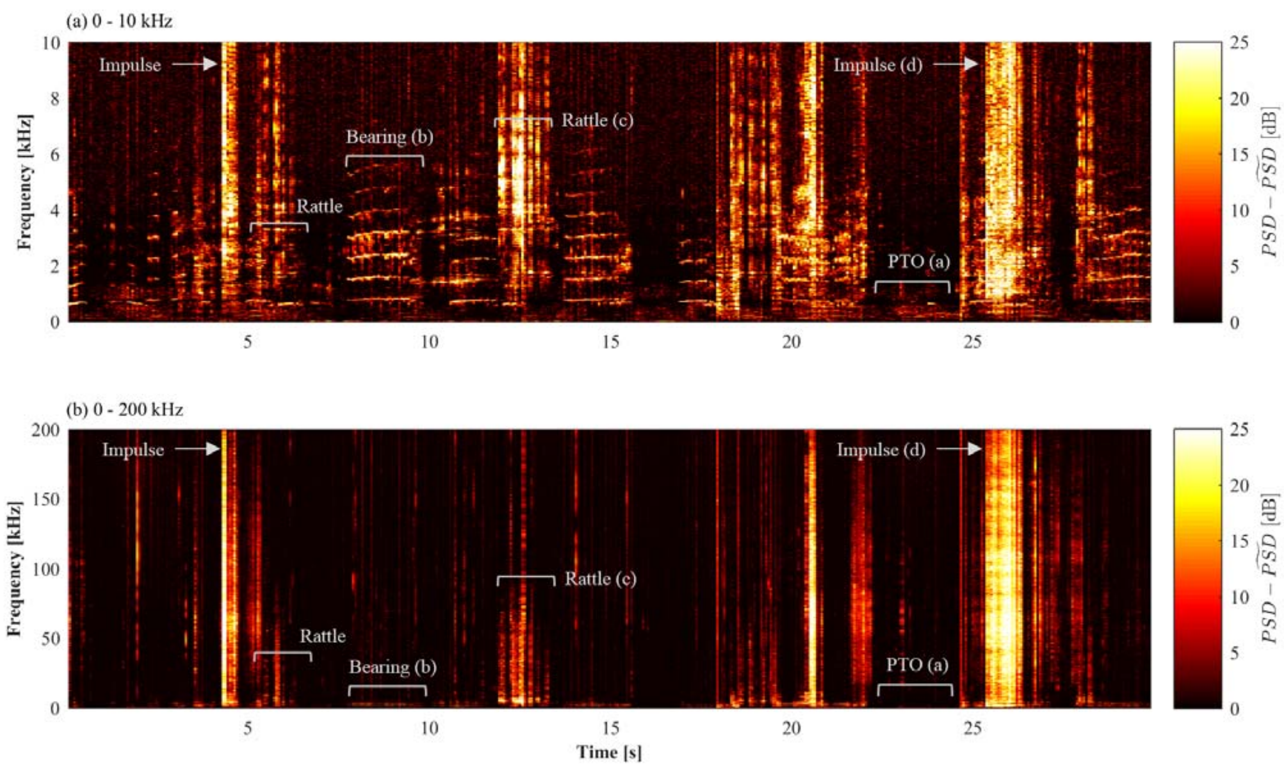

Fig. 9 Spectrograms from January 2017 (Drift 4). (a) Detail from 0 – 10 kHz. (b) Full frequency range from 0 – 200 kHz. Distance to WEC is ~35 m.

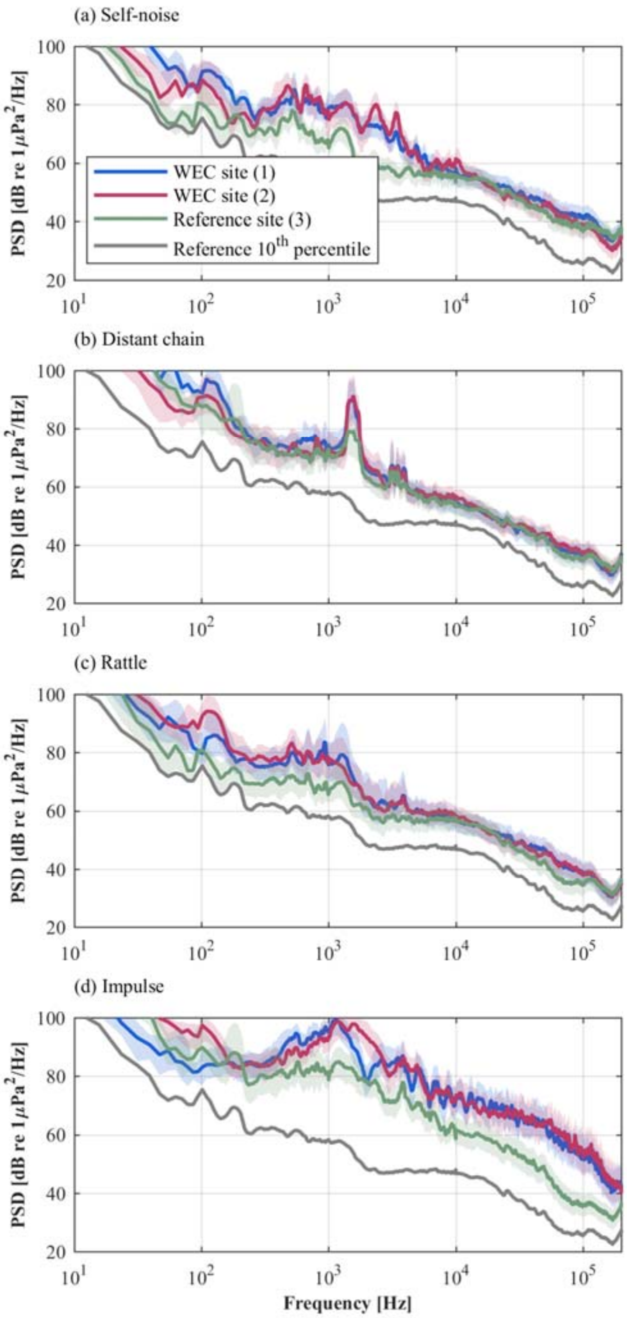

Fig. 10 Periodograms from annotated events in Fig. 8. The thick line is the median PSD for the event (duration indicated in Fig. 8), while the transparency denotes the inter-quartile range. All spectra are co-temporal with the event, except for the grey line which denotes the 10th percentile PSD for the entirety of the 30-s window at the reference site to visualize the deviation from quiet conditions. Distance to WEC is ~70 m.

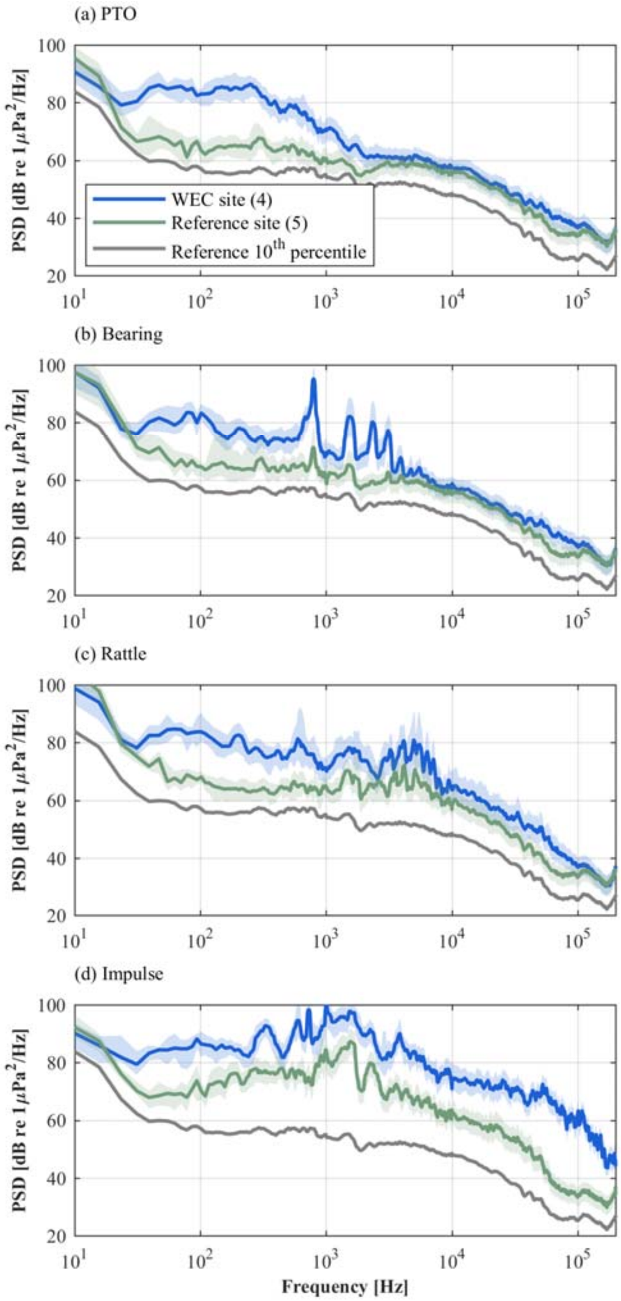

Fig. 11 Periodograms from annotated events in Fig. 9. Distance to WEC is ~ 35 m.

avoid significantly overstating source levels[2].

[2] The permit under which WETS operates requires source levels to be roughly estimated by geometric spreading for regulatory reporting purposes. If broadband sound pressure levels associated with a WEC are found to exceed 154 dB for more than 5% of the operating time, NOAA's National Marine Fisheries Service must be immediately notified. However, if one ascribes all received levels to a WEC, the geometric amplification of non-propagating flow-noise artificially inflates such an estimate. This is particularly problematic for stationary platforms deployed at greater range from the WEC and/or in shallower water where average wave orbital velocities are higher at the seabed, producing more flow-noise.

D. Sea State Dependence

A comparison of the broadband sound pressure level (SPL) to co-temporal significant wave height and energy period (Fig. 14.a) suggests a dependence of received levels on sea state. Further separation of received levels by sea-state and frequency band helps to identify the underlying sources for this dependence. Sound at frequencies below 10 Hz (b) is the dominant source of energy in the broadband SPL and is strongly correlated with significant wave height. The source of this sound is likely flow-noise driven by wave orbital motion. As discussed in Section IV.B, the bearing warble has a fundamental frequency around 790 Hz, and sound levels in this band also exhibit sea state dependence (c). Because the Lifesaver is tuned to operate efficiently over a range of sea states, it is logical the sound from a damaged PTO component would show a similar sea state dependence. Sound between 5 and 40 kHz (d) is dominated by mooring noise and snapping shrimp. While the former is dependent on sea state, the calculation of mean spectra over long time windows (relative to the duration of mooring noise) and the subsequent ensemble averaging reduce the influence of episodic events. As a consequence, this band has a limited dependence on sea state.

V. Discussion

The episodic nature of sound around the Lifesaver and temporal evolution of these sounds over the deployment create a number of challenges to quantitatively describe the acoustic environment and definitively ascribe sound at specific frequencies to the Lifesaver. As shown in Fig. 13, the median PSD (solid black line) is primarily a composite of the most frequently occurring events in a drift (in this case, sound from the PTO and damaged bearing). Median statistics minimize the potential bias introduced by infrequent, high-amplitude events (e.g., metallic impulses from the permanent moorings), as do the ensemble averages used to describe temporal statistics. Mean statistics (Fig. 13, dashed black line) are substantially altered by these events. Similarly, if Sound Exposure Level (SEL) [14], rather than SPL, is used as an assessment metric, the infrequent, higher-amplitude sounds would have a limited contribution over the long integration period.

Median statistics do not, however, differentiate between persistent WEC sound and co-temporal sounds with similar persistence and frequency content, such as the vocalizations of humpback whales (which are present in many of the manually-reviewed stationary measurements). Consequently, segregation of sample windows that contain uncontaminated, persistent events associated with the WEC could further elucidate sea state dependencies in stationary measurements and range dependencies in free-drifting measurements. Although it is possible to undertake a manual analysis of this type for limited portions of the dataset, this would be infeasible to conduct for all recordings. However, the distinctive structure and duration of the various sounds observed in the vicinity of the Lifesaver (Fig. 13) suggest that machine learning classification may be an effective method to

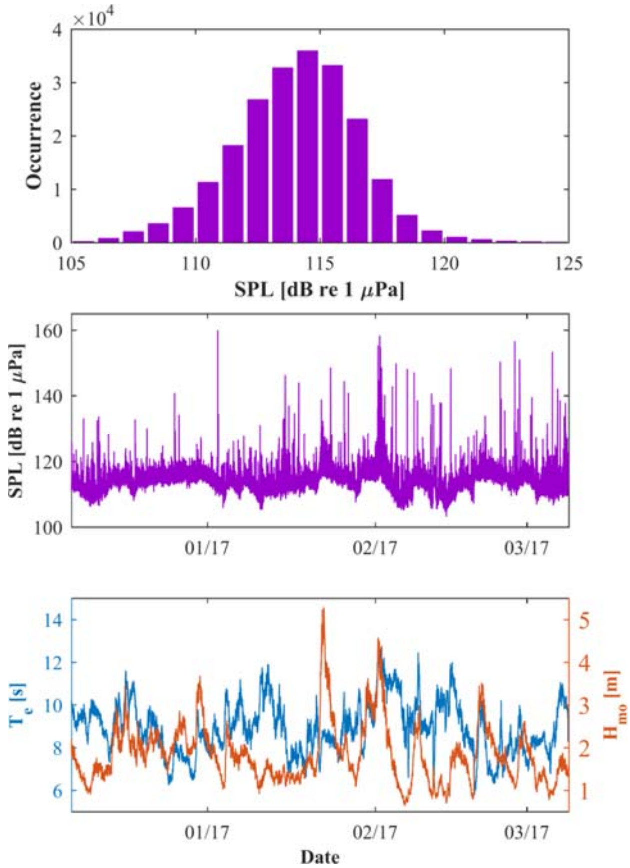

Fig. 12: Histogram of broadband SPL over Sea Spider deployment (top). Broadband SPL (middle) and co-temporal significant wave height (H_{m0}) and energy period (T_e) (bottom).

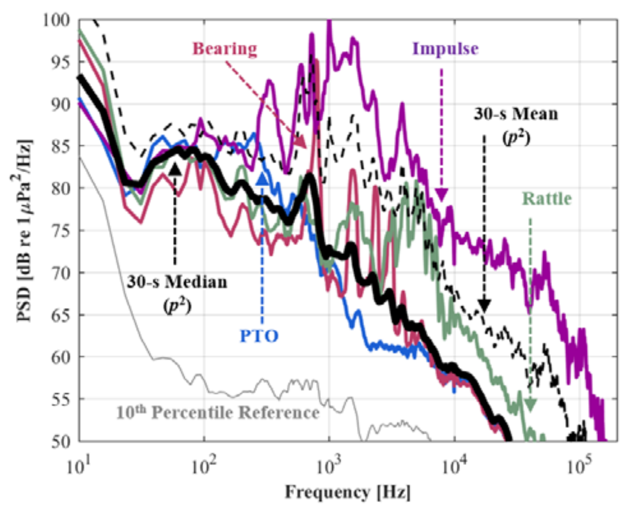

Fig. 13 Periodograms of episodic sounds (Drift 4, Jan. 2017), the median of the 30-s sequence in pressure-squared space, the mean of the sequence, and the 10^{th} percentile from the reference case (Drift 5).

achieve this and an obvious next step.

Free-drifting measurements are found to have a number of benefits. First, the shorter duration allows higher frequencies to be more easily resolved, which can be helpful to design stationary surveys where storage is more constrained. This information can also help to understand the likelihood of sounds being detected by marine animals with hearing specialization (e.g., dolphins). Second, free-drifting measurements can be used to establish range dependence of specific sounds and help to identify their source. In particular, co-temporal reference measurements at moderate distance (e.g., > 1 km) have significant value in identifying sound originating from a specific source. While not shown here, multiple co-temporal DAISYs spread between the unoccupied 80 m berth and the Lifesaver at the 60 m berth were used to confirm that the 1.5 kHz peak observed consistently in the spectra was, in fact, originating from the 80 m berth. However, unless a free-drifting hydrophone is mechanically de-coupled from its surface expression, flow-noise and self-noise can introduce significant uncertainty in the interpretation of received levels at frequencies below a few hundred Hz, where WECs are likely to produce most of their acoustic emissions in normal operation. While a mass-spring-damper system between the surface expression and hydrophone was effective at achieving this isolation, this benefit was not without its drawbacks. The DAISYs with rigid spars were able to cleanly drift past the Lifesaver, while, to avoid entanglement, the DAISYs with compliant couplings needed to be deployed to the down-wave side of the hawser lines trisecting the site (Fig. 2). Overall, free-drifting measurements are an important complement to stationary observations, which are able to characterize sounds over a longer duration and in more extreme sea states.

VI. Conclusions

A combination of free-drifting and stationary measurements were used to characterize the sound in the vicinity of the Lifesaver wave energy converter. Sounds were episodic and temporally evolved over the study. A weak dependence on sea state is observed for some frequency bands, most pronounced around frequencies associated with flow-noise and a damaged PTO component. While an emphasis is often placed on an improved understanding of the sound produced by WECs, in this case, were all PTOs on the Lifesaver to be operating normally, sound production would be largely limited to less than 250 Hz. Damage to the PTO bearing was clearly audible at higher frequencies (up to 5 kHz) and at ranges greater than 1 km, emphasizing the benefits of incorporating passive acoustics into condition monitoring of marine energy conversion systems. In contrast to expectations, the observed sounds with the highest amplitude relative to the background originated not with the WEC or its PTOs, but with the mooring system, which is a three-point mooring provided by WETS independent of the WEC under test. This highlights a need for system engineering approaches that can reduce the acoustic footprint of wave energy conversion systems, while maintaining efficient operation across a range of sea states.

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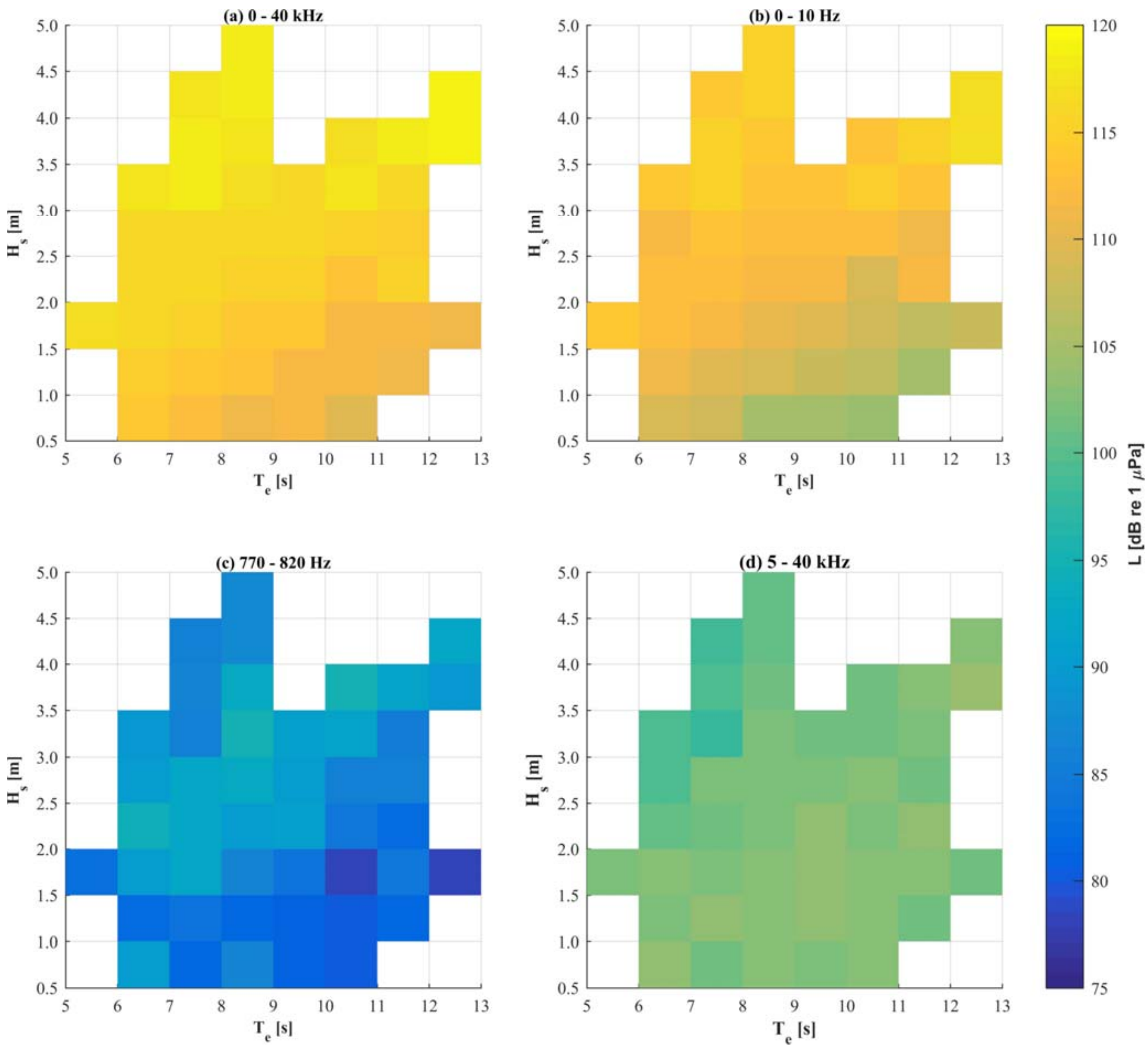

Fig. 14: Stationary platform received level as a function of sea-state and frequency band. (a) broadband sound pressure levels (0 - 40 kHz), (b) band levels dominated by flow-noise (0 - 10 Hz), (c) band levels dominated by sound from damaged PTO bearing (770 – 820 Hz), (d) band levels dominated by snapping shrimp and metallic impulse from the permanent moorings (5 - 40 kHz).