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HYDROACOUSTIC MEASUREMENTS OF THE NOISE RADIATED FROM WAVE ENERGY CONVERTERS IN THE LYSEKIL PROJECT AND PROJECT WESA.

Kalle Haikonen[a], Jan Sundberg[a] and Mats Leijon[a].

[a] Uppsala University, Div. of electricity, Box 534, 751 21 Uppsala, Sweden

Kalle Haikonen
Uppsala University
Div. of electricity
Box 534
751 21 Uppsala
Tel: +4618-5818
Fax: +46184715810
Email: kalle.haikonen@angstrom.uu.se

Abstract: *Field measurements of the hydroacoustic noise from Wave Energy Converters (WECs) in the Lysekil project at Uppsala University and the Project WESA (joint effort between Uppsala University (Lead Partner), Ålands Teknikkluster r.f. and University of Turku) are presented. Anthropogenic noise is increasing in the oceans world wide and wave energy conversion may contribute to this noise, but to what extent? The main objective in this study is to examine the noise from full scale operating WECs in the Lysekil and project WESA. Acoustic measurements were made in order to be able to estimate potential environmental impact. Submersible recording devices (SRD) were deployed at 1 m from WECs at a depth of approximately 24 meters. Both WECs are a full scale point absorber with a directly driven linear generator, placed on gravitation foundations at the seabed with a connected buoy at the surface that absorbs energy from the heaving waves. The SRDs used to measure the noise from the WECs, consists of a SM2-recorder from Wildlife Acoustics and hydrophones from High Tech Inc. (HTI 96 MIN and HTI 99 HF). Measurements at in the Lysekil project were carried out in the spring of 2013 and in the project WESA in Jan-Feb of 2012. Preliminary results show that the main operating noise radiated from the WEC are short transients with instant rise time when the translator moves past the stator and when the stator hits the end stop springs of the generator. Most of the power in the noise is between 20 – 1000 Hz.*

Keywords: *Wave Energy Converter, Underwater noise, renewable energy.*

1. INTRODUCTION

Underwater noise levels in the oceans have been rising considerably during the last century. Several studies conclude that most of the noise derives from shipping activity [1, 2, 3], but all anthropogenic activities (recreational boats, pile driving, vibration from bridges, oil drilling, wind power etc.) in the ocean contribute to ambient noise levels in some degree. Little is known of the effects of different anthropogenic sounds in the ocean, and the concern about the effects on marine life is increasing [4, 5, 6].

The idea of wave energy conversion has existed for many years, but only *recently* have concepts such as Pelamis, Archimedes Wave Swing, Wave Dragon and the Lysekil Project, actually been tested in real offshore environment [7, 8, 9, 10], and are closing in on full scale commercial wave energy parks. Wave energy parks may become an additional source of underwater noise. While individual devices are not expected to radiate a high level of noise, the deployment of a large-scale park may have an effect on the fauna [11]. The marine environment is a sensitive environment and it is important to early identify potential environmental impacts (negative and positive) and the source of the disturbance. This may lead to changes in WEC design to minimize the impact on the environment. Few environmental studies that concerns WECs and refer to field data are available, but there are studies concerning WECs and artificial reef effect. An increase in biomass and biodiversity was shown locally around the WEC. Both fouling and motile species contributed to this increase [12, 13]. This increase can be explained by the addition of species associated with hard bottoms to a soft bottom area.

The characteristics of the noise radiated by an operating WEC will surely differ between different WEC concepts. The deployment of two full scale WECs in the Lysekil (L12) and WESA (WESA) projects offers the possibility to study the noise from WECs of this particular concept: direct driven linear generators with a surface point absorber. This study presents preliminary results of the noise radiated from these two WECs which have some design differences between them. The main purpose of this study is to identify the source and characteristics (spectral level, sound pressure level (SPL), sound duration and repetition rate) of the operational noise from the L12 and WESA.

1.1. Wave Energy Converter Description

The L12 and WESA are based on a point absorber system with a directly driven longitudinal permanent magnet linear generator, placed on a concrete foundation at the seabed with a connected buoy at the sea surface that absorbs energy from the heaving waves (Fig 1.1) [10, 14]. Through a steel wire and a guiding system this energy is transmitted to the translator inside the generator. The translator is equipped with permanent magnets between aluminium spacers, these induce voltage as they pass the windings in the stator of the generator, thereby converting some of the energy from the waves into electric energy. At the top and bottom on the inside of the generator end stop springs are placed as dampers, in order to handle mechanical overload and translator stroke length in sea states that are higher than design conditions. The varying speed and direction of the translator causes variation in both frequency and amplitude of the output current and voltage. Clusters of WECs has to be interconnected through an underwater substation to manage this [15, 16]. There is a difference translator and in the end stop design between the WECs; in the WESA the end stop springs are plate springs (Fig. 1.2a) and in the L12 they are mechanical springs (Fig. 1.2b). Also there is a difference in the translator and stator design. The translator area facing the stator is greater in the L12 giving it higher power (L12 = 30 kW and WESA = 15 kW), and it moves on guiding wheels directly mounted on the outer shell, in contrast to WESA where the guiding wheels are mounted on a frame that has no direct contact with the outer shell. A detailed description of the Lysekil project and direct driven WECs are found in [10, 14].

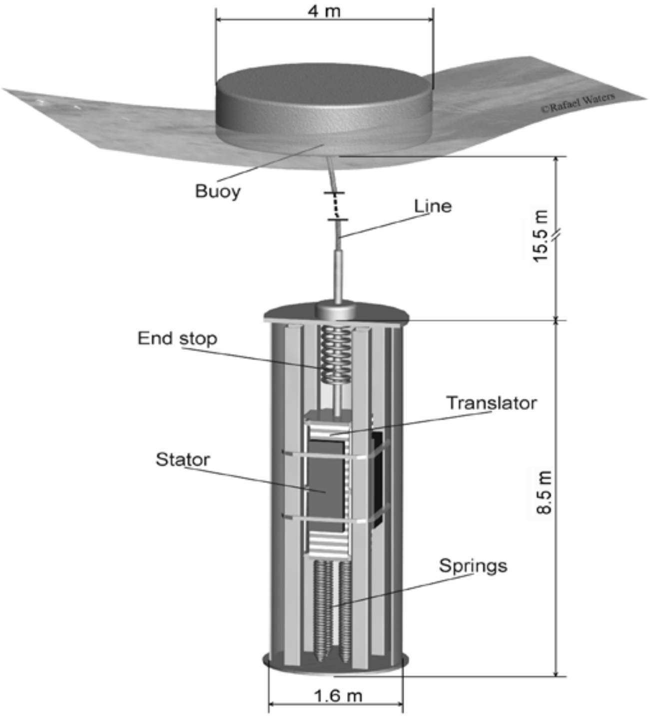

Figure 1.1: Representation of a direct driven linear WEC

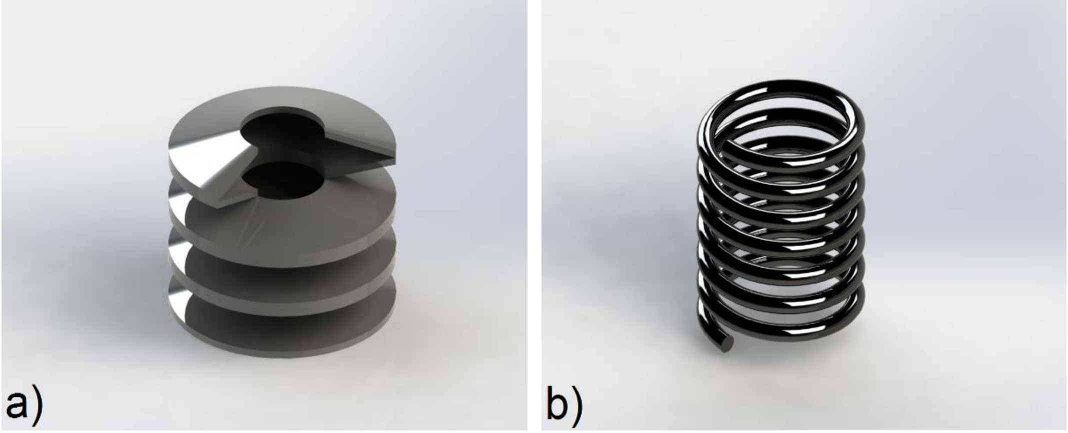

Figure 1.2: Representation of the end stop springs in the WECs. a) Plate spring, used in WESA. b) Mechanical spring, used in L12.

2. MATERIAL AND METHODS

2.1. Field sampling

Underwater noise was recorded from two WECs in this study. Digital measurements were made with a submersible recording device (SRD). Measurements in the Lysekil project were performed during Mar-May 2013, and in the project WESA during Jan-Feb 2012. In both projects there was one operating WEC in the area during the measuring periods.

2.1.1. The Lysekil Project

The SRD was deployed at a depth of 24m, on the concrete foundation at 1 m from the WEC in the *Lysekil research site*, which is located at the Swedish west coast 1 nm offshore (58° 11' 44.12" N, 11° 22' 22.50" E. The depth in the area ranges between 24 and 26 meters, and the seabed consist of sand and silt [18].

The SRD consisted of a Song Meter 2 (SM2) recording platform (Wildlife Acoustics Inc.) with 16-bit recording technology and hydrophones from High Tech Inc. (HTI). Two different hydrophones (tab. 1) functioned as the sensors of the SRD.

Table 1: Specifications of the hydrophones used.

Hydrophone	Frequency range (flat) (Hz)	Sensitivity (dB re 1V/ µPa)
HTI-96-min	2 - 30000	-165
HTI-99-HF	2 - 125000	-181

A gain of +12 dB was set to the left channel (HTI 96-min), which gave this channel a sensitivity of -153 dB re 1 µPa. No gain was set the right channel (HTI-99-HF). The total dynamic range of the SRD was -63 to -181 dB re 1 µPa. The SRD was programmed to record 5 min in the beginning of every hour, sampling rate was 48 kHz. The measurements on the radiated noise from the L12 in this study are from 4 different 5 min measurements between 14th and 24th April 2013. The digitized sound was stored in WAV-format on SDHC memory cards in the SM2. An error in +/- 1dB is estimated to occur in the SM2 digital conversion process. The recording device was calibrated with the HTI-96-min by the supplier (Wildlife Acoustics). An underwater housing was made for the SM2 platform and the hydrophone was suspended outside of the underwater housing.

In the *Lysekil research site*, in close vicinity (approx. 120m) to the L12, a wave measuring buoy **(**Waverider Fl) from Datawell BV Oceanographic Instruments was located. The wave measuring buoy continuously measured the wave height, and the significant wave height (SWH) was calculated for every 30 min.

2.1.2. The project WESA

The *WESA research site*, is located approx. 0.4 nm offshore, west from Hammarudda on the main island of Åland at 60˚ 06' 19.68” N, 19 ˚ 43' 45.78” E. The depth where the WESA is located is 25m, and the seabed consist of sand and till [19].

The SDR was deployed the concrete foundation at a distance of 1m from the WESA, at a depth of 24 m. The SDR was of the same type that the one on the L12 (SM2, underwater housing and HTI hydrophone), with the difference that the SDR only had one hydrophone: HTI-99-HF (see Tab. 1). No gain was set to the hydrophone so the dynamic range of the SRD was -91 to -181 dB re 1 µPa. The SRD was programmed to record 5 min in the beginning of every half hour min and sampling rate was 48 kHz. The digitized sound was stored in WAV-format on SDHC memory cards in the SM2. An error in +/- 1dB is estimated to occur in the SM2 digital conversion process. The SRD was calibrated with a HTI-96-min prior the measurements by the supplier (Wildlife Acoustics).

During the period of the measurements there was no wave measuring buoy in the vicinity of the WESA. It had been retrieved prior to the noise measurements due to the risk of ice in the area. Wave data during the measuring period was provided by the Finnish Meteorological Institute, from a wave measuring buoy at a distance of approx. 12 km from WESA. The data gave wind speed, wind direction and SWH per half hour. This data together with ambient noise levels (ANLs) and noise emitted from the WESA, was used to do a rough estimation of the SWH during the measurements in this study: Low = SWH of 1.5 ± 0.15 m and High = SWH of 2.5 ± 0.5 m.

2.2. Acoustical analysis

The sounds from the WECs were categorized depending of the SWH. Two different SWHs (0.5 and 1.5 m) were chosen in the Lysekil measurements and two SWHs (Low and High) were roughly estimated for the WESA measurements.

The frequency analysis was performed with FFT (Fast Fourier Transform) and is presented in 1/3 octave levels (dB re 1 µPa) which has been suggested when comparing noise spectrums with pure tone audiograms of marine species [20]. The frequency analysis was made in frequencies between 20 Hz – 20 kHz. All WEC noise sound pressure levels (SPL) are at 1m (source level (SL)) and are given in dB re 1 µPa. Noise range, the distance it takes for the overall noise SPL to reach ANLs was roughly estimated by using the equation for practical spreading law, where transmission loss (TL) was stated as the difference between SL and ANL:

$$TL = SL - ANL = 15\log(R) \tag{1}$$

$$R = 10\hat{}\left(\frac{TL}{15}\right) \tag{2}$$

where R is the distance and the factor 15 represents an intermediate spreading condition between spherical spreading (a factor of 20) and cylindrical spreading (a factor of 10) [21, 22].

3. RESULTS

Preliminary results shows that there are two main noises emitted from the WECs, both transient noises, but with different characteristics. One noise originates from when the translator moves up and down past the stator and the other originates when the translator hits the end stop springs (upper or lower). The noise from the moving translator (MT) occurs in all analysed measurements, but the end stop hit (ESH) only occurs if waves >2.0m p-p pass the surface buoy of WEC (which may start to occur in SWH > 1.0m). Then the full stroke length of the WEC is utilised and the end stop springs damp the motion of the translator. In this preliminary study only one MT noise per 5 min recording was analysed (the one with highest power). The ESH noise only occurred once in the SWH 1.5m and Low. In the SWH High, ESHs were repeated 53 times in 5 min. 39 of the 53 ESHs exceeded the maximum signal level of the recording devices (181 dB re 1 µPa). When this happened the signal was clipped and the signal was distorted. No such signals were analysed further. The ESH analysed in the SWH High, was the one was the highest undistorted signal during that recording. The ambient noise was measured directly after an analysed MT or ESH when there was no noise from the WEC.

The rise time (time required for the signal to reach full power) of the MT was between 0.5-0.65 s, and the total duration of the noise was between 1.3 - 1.5 s. There was a difference in both amplitude and spectrum levels between the MT noise of L12 and the WESA. In the L12 the MT noise was measurable above the ANL over the entire analysed frequency range (20 Hz–20 kHz), with highest amplitudes in frequencies < 1000Hz, with peak amplitude at 100 Hz (SWH: 0.5 m) (Fig. 3.1a) and 31.5 Hz (SWH: 1.5 m) and (Fig. 3.1b). The WESA MT noise was only measurable over ANL below 100 Hz (Low) (Fig. 3.1c) and 300 Hz (High) (Fig 3.1d). There was a difference in amplitude, with considerably higher amplitudes from the L12, both spectral and overall noise (Tab. 2).

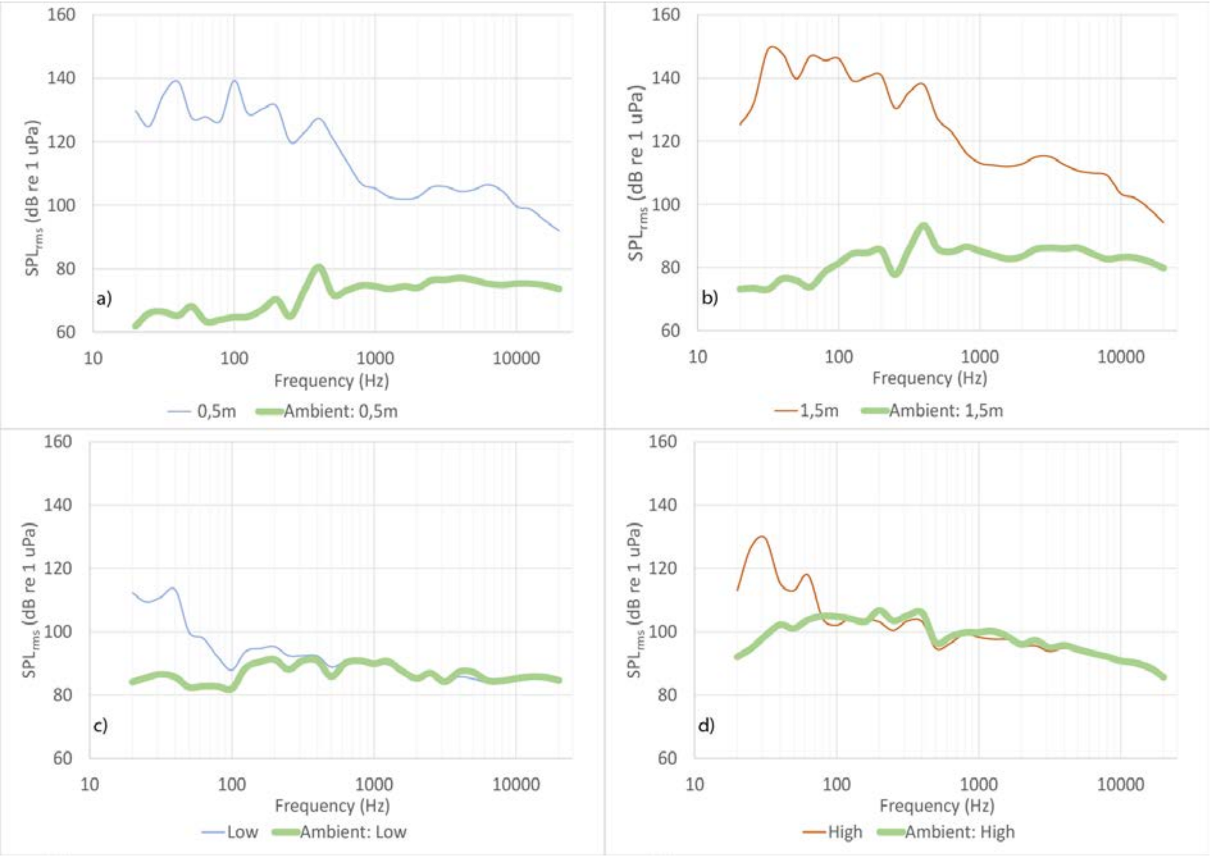

Fig. 3.1: Spectrums of the MT noise from the L12 and WESA. Frequency (Hz) on the x-axis and sound pressure level root mean square (dB re 1 µPa) on the y-axis. a) L12 MT noise in SWH 0.5m (blue line) and ambient noise in 0.5m SWH (green line). b) L12: MT noise in SWH 1.5m (brown line) and ambient noise in 1.5m SWH (green line). c) WESA MT noise in Low (SWH 1.5 ± 0.15m) (blue line) and ambient noise in Low (green line). d) WESA MT noise in High (SWH 2.5 ± 0.5m) (brown line) and ambient noise in High (green line).

The ESH noise has an instant rise time and then the amplitude rapidly decreases. The duration of the ESH noise was between 0.2 – 0.3 s. The ESH noise was clearly measurable above ANLs over the entire analysed frequency range in all cases (1.5m, Low and High). In the ESH of SWH 1.5 m and Low most of the energy was in frequencies < 500 Hz, with peak amplitudes at 100, 400 and 500 Hz (1.5 m) (Fig. 3.2a) and at 125 Hz (Low) (Fig. 3.2b). In the WESA the amplitudes in all frequencies above 200 Hz were higher in SWH High compared with SWH Low. In SWH High peak amplitudes were at 315 and 1250 Hz (Fig. 3.2c). This indicates that wave height alters the ESH noise from the WESA considerably. In SWH High the ESH noise always came in two: first when the end stop spring was decompressed, followed by a second with lower amplitude when it elongates. The spectrum levels were the same for both transients. This was not observed in the ESH of Low or L12. A comparison between the different ESH are found in Fig 3.2d. There was also a difference in amplitude, with higher amplitude with increasing wave height (WESA), but also between the WECs, with higher amplitude in the L12 (Tab.2).

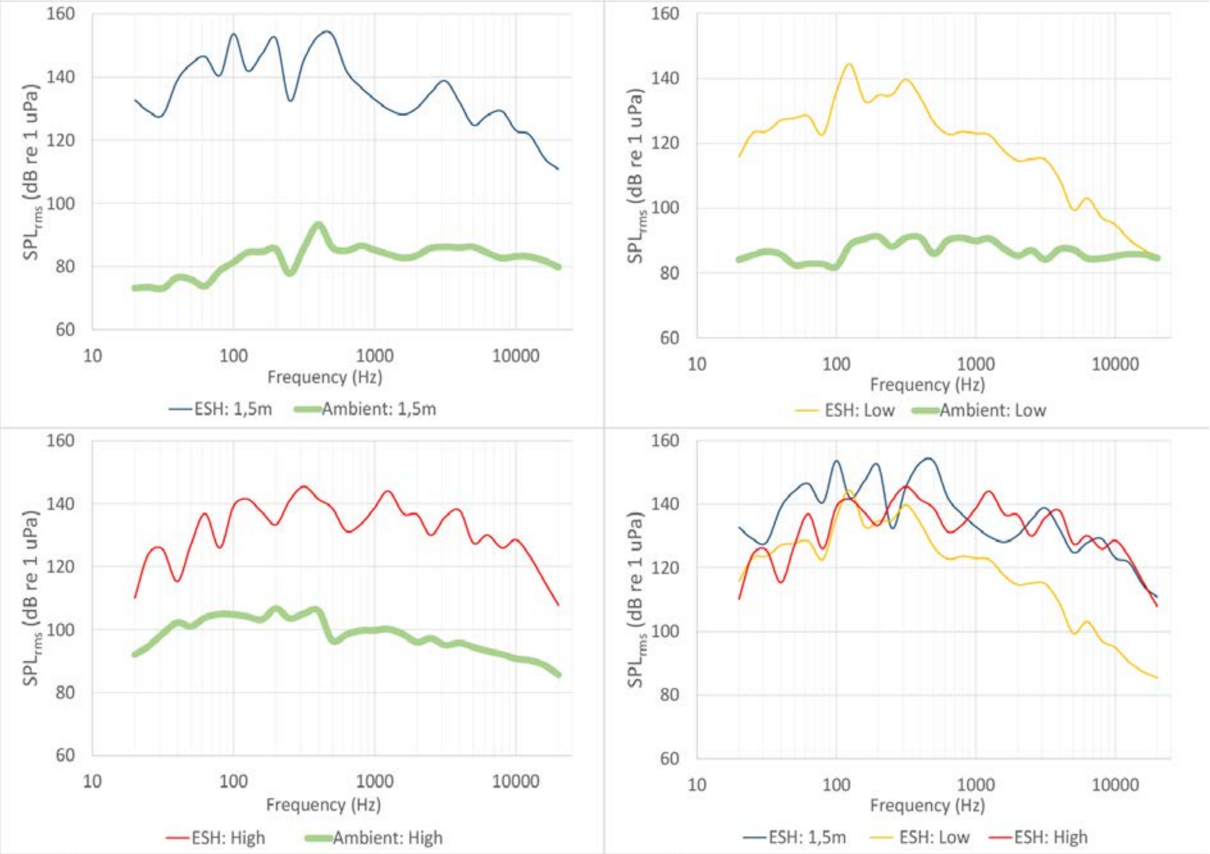

Fig. 3.2. Spectrums of the ESH noise from the L12 and WESA. Frequency (Hz) on the x-axis and sound pressure level root mean square (dB re 1 µPa) on the y-axis. a) L12 ESH noise in SWH 1.5m (blue line) and ANLs in SWH 1.5m (green line). b) WESA ESH noise in Low (SWH 1.5 ± 0.15m) (yellow line) and ANLs in Low (green line). c) WESA ESH noise in High (SWH 2.5 ± 0.5m) (red line) and ANLs in High (green line). d) Comparison between all ESH: L12: SWH 1.5 (blue line), WESA: Low (yellow line) and WESA: High (red line).

Table 2. Summary of WEC and ambient noise measurements. Shown are noise type: Moving Translator (MT) and End Stop Hit (ESH), Significant Wave Height (SWH), overall sound pressure level (SPL), noise duration, ambient noise level (ANL), estimated range for the noise to reach ambient noise levels.

WEC	Noise Type	SWH (m)	Overall SPL (dB re 1 µPa)	duration (s)	ANL (dB re 1 µPa)	Estimated Range (m)
L12	MT	0.5	144	1.3	89	5400
L12	MT	1.5	155	1.3	101	4000
WESA	MT	Low	118	1.5	104	10
WESA	MT	High	131	1.3	116	10
L12	ESH	1.5	160	0.2	101	8600
WESA	ESH	Low	149	0.3	104	1000
WESA	ESH	High	159	0.2	116	735

4. DISCUSSION

The underwater noise from the WECs had two main operational noises (both transient); 1) when the translator moved past the stator in the generator (MT) and 2) when the translator hit the end stop springs in top or bottom in the generator. The MT noise was measurable above the ambient noise at 1m from the WECs in all analyzed wave heights. L12 MT noise levels ranged between 144 and 155 dB re 1 µPa_{rms} (54 – 55 dB re 1 µPa_{rms} above ANL). WESA MT noise levels ranged between 118 and 131 dB re 1 µPa_{rms} (14 – 15 dB re 1 µPa_{rms} above ANL)

The ESH noise only occurred in the measurements with SWH ≥ 1.5m. This was expected since the translator has a free stroke length of 2.0m, and waves > 2.0m_{p-p} are not expected in SWHs < 1.0m. The ESH noise was clearly measurable over the ambient noise in all analysed frequencies. The ESH noise from the High measurement has significantly higher amplitudes in all frequencies > 1000 Hz, also the amplitude is higher. The later statement was expected due to the higher kinetic energy that has to be dampened in periods with higher waves. L12 ESH noise level was 160 dB re 1 µPa_{rms} (59 dB re 1 µPa_{rms} above ANL). WESA ESH noise levels ranged from 149 – 159 dB re 1 µPa_{rms} (43 – 45 dB re 1 µPa_{rms} above ANL)

The higher amplitudes in both MT and ESH of the L12 were not expected so great. The translator moves on wheels which enables a smooth motion up and down for the translator. One reason for the higher values in the MT noise of L12a could be that the vibrations in the guiding wheels (caused by the moving translator) radiates directly to the outer shell from where it radiates into the water.

The ESH noise was expected to be lower in the L12 since the mechanical springs were thought to dampen the translator more smoothly, however the noise level was higher. Examining a WEC (same design as the L12) under construction, it was revealed that design of how the springs were attached to the generator gave a gap between spring and generator, in which the spring could move. This might have been a contributing factor to increased noise.

The spectrum levels and transient number of the WESA ESH noise changed with increasing wave height (higher amplitudes in frequencies > 1000Hz and two transients each time the translator hit the springs), if this also is the case with the ESH noise from the L12 is still not known.

These are preliminary results of the characteristics of the noise radiated from WECs in the Lysekil project and project WESA. The maximum SPL from the different noises are not yet determined, but it seems that the MT noise will not be more than approx. 15 dB re 1 µPa above ANL at 1m from the WEC and have been reduced to ANLs at 10 m from the generator (if the translator can pass the stator without any contact). The maximum SPL of the ESH noise was not determined, in measurements on the L12 the SWH did not surpass 1.5m and in the WESA the measuring equipment which had a maximum signal level of 181 dB re 1 µPa was overloaded in the measurement with the highest SWH. At a SWH of 1.5 ± 0.15 m the ESH noise will not reach ANLs until 1000 – 8600 m from the WEC.

In the design of both analysed WECs there was metal to metal contact when the translator hit the end stop. Noise levels would probably be reduced if the damping of the translator could be smoother or if direct metal to metal contact could be eliminated. These measurements have led to alterations in the design of the WEC L12b. Softer materials will be used as insulation between translator and stator.

Future work includes measurements at different distances to examine how the noise propagates in the wave power sites.

5. ACKNOWLEDGMENTS

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