Energies **2013**, *6*, 2562-2582; doi:10.3390/en6052562

OPEN ACCESS

energies

ISSN 1996-1073

www.mdpi.com/journal/energies

Article

Characteristics of the Operational Noise from Full Scale Wave Energy Converters in the Lysekil Project: Estimation of Potential Environmental Impacts

Kalle Haikonen *, Jan Sundberg and Mats Leijon

Division of Electricity, Uppsala University, P.O. Box 534, Uppsala 751 25, Sweden;
E-Mails: jan.sundberg@angstrom.uu.se (J.S.); mats.leijon@angstrom.uu.se (M.L.)

* Author to whom correspondence should be addressed; E-Mail: kalle.haikonen@angstrom.uu.se;
Tel.: +46-18-471-5818; Fax: +46-18-471-5810.

Received: 5 February 2013; in revised form: 10 May 2013 / Accepted: 14 May 2013 /
Published: 21 May 2013

Abstract: Wave energy conversion is a clean electric power production technology. During operation there are no emissions in the form of harmful gases. However there are unsolved issues considering environmental impacts such as: electromagnetism; the artificial reef effect and underwater noise. Anthropogenic noise is increasing in the oceans worldwide and wave power will contribute to this sound pollution in the oceans; but to what extent? The main purpose of this study was to examine the noise emitted by a full scale operating Wave Energy Converter (WEC) in the Lysekil project at Uppsala University in Sweden. A minor review of the hearing capabilities of fish and marine mammals is presented to aid in the conclusions of impact from anthropogenic sound. A hydrophone was deployed to the seabed in the Lysekil research site park at distance of 20 and 40 m away from two operational WECs. The measurements were performed in the spring of 2011. The results showed that the main noise was a transient noise with most of its energy in frequencies below 1 kHz. These results indicate that several marine organisms (fish and mammals) will be able to hear the operating WECs of a distance of at least 20 m.

Keywords: direct driven wave energy converter; underwater noise; environmental impact; renewable energy

---

1. Introduction

Wave energy conversion is a potential clean electric energy conversion with no emissions during operation. Still there are issues considering impacts on the environment regarding sounds, electromagnetism and artificial reef effect that need to be examined. Few studies exist on these topics since wave energy conversion is a relatively new technology. Wave energy conversion has existed for many years but only recently different concepts such as Pelamis, Archimedes Wave Swing (AWS), Wave Dragon and the Lysekil Project, has actually been tested in real offshore environment [1–4]. Environmental studies on these different techniques are needed to get a truly sustainable source of energy. There are some studies on environmental effects concerning Wave Energy Converters (WECs) and artificial reef effect. They have shown an increase in biomass and biodiversity locally around the WEC. The increase can be explained by the addition of hard bottom species to the area. Fouling species contributed the most the increased biodiversity, but also motile organisms such as different species of fish and crustaceans [5,6]. Submerged structures will inevitably attract marine organisms adapted to hard bottoms that will colonize them. This will happen either by settling or migration. An increase in biodiversity, species abundance and biomass may occur locally [7–9]. This is due to the hard surface that many organisms need to survive, which is offered by the WECs. Although a WEC offers hard substrate for organisms to settle on which in turn attracts more free swimming organisms, the WEC is not a silent substrate. The operation of the WEC will produce vibrations and sounds which may affect the surrounding marine life.

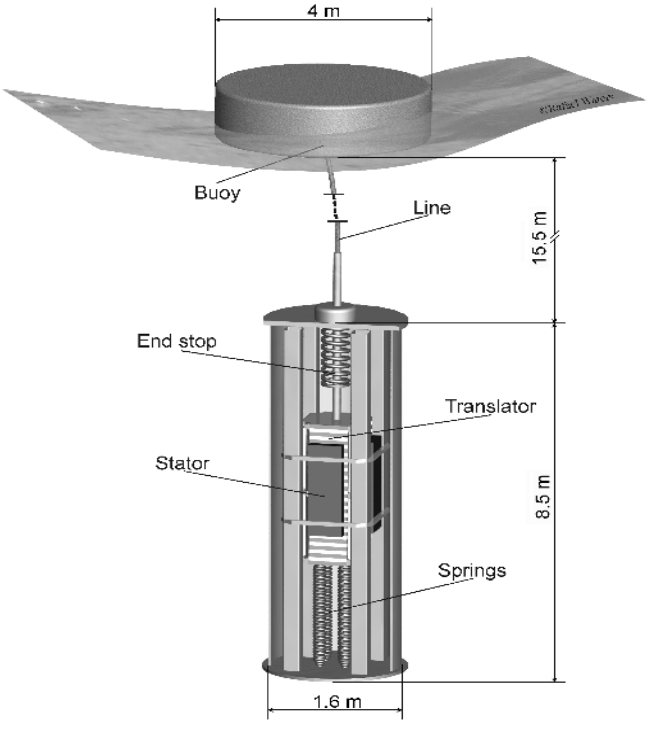
Anthropogenic noise is increasing in the oceans and shipping alone has increased the ambient noise by 12 dB (re 1 μPa) over the past few decades [10]. Little is known of the effects of different anthropogenic sounds in the ocean, but the concern about the effects on fish and marine mammals is increasing [11–13]. Ambient noise is the background noise in the ocean and is the sound field against which signals must be detected. It consists of both natural (e.g., wind, waves, seismic activity) and anthropogenic (e.g., shipping, pile driving, bridges, wind power) sounds. Wave power will contribute to the ambient noise in the oceans, both locally and globally, but to what extent?

To determine whether a particular sound is disturbing or even harmful to marine organisms is difficult since the auditory characteristics differ greatly between marine organisms. Different species can perceived a specific sound in different ways [14]. There are studies that have examined how pile driving and offshore wind affects fish, both their behavior and physical well being [15–18]. The results from these studies are difficult to apply to other sound sources, as they may differ in amplitude, frequency range and duration. There are indications that sound may cause some kinds of effects on marine organisms, but how and to what degree depend on the species and conditions. Extrapolation between different sounds and different species is not possible. Thus, it is difficult to determine what effect a sound will have on the environment. The basic need is for a set of systematic studies that examine effects of highly quantified sounds of various types (e.g., different types of pile driving, different seismic sources, *etc.*) on a wide range of morphologically and taxonomically diverse species of interest [13]. The main objectives of this study is to examine the sound emitted from operating WECs in the Lysekil project, and evaluate the impacts of this noise on marine organisms. Characteristics such as spectrum level, sound pressure level (SPL), duration and repetition rate are all important to describe a sound source [10]. These characteristics will help to evaluate if marine organisms might be affected by the sound of an operating WEC and if the sound will be local or widespread.

2. Wave Energy Converter Description

The WECs in these hydroacoustic measurements were point absorbers with a directly driven longitudinal flux one-phase permanent magnet synchronous 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 (Figure 1) [4,19]. Through a steel wire and a guiding system this energy is transmitted to the translator inside the generator. Springs are attached between the bottom of the translator and the generator foundation, in order to retract the translator to keep tension in the wire to the buoy in the wave troughs. The translator is equipped with Neodymium-Iron-Boron permanent magnets that are mounted between aluminium spacers, these induce voltage as they pass windings in the stator of the generator, thereby converting some of the energy from the waves into electric energy, and the remaining energy is stored in the retracting springs. This energy is converted into electricity as the springs pull the translator down past the stator windings in the following wave trough. At the top and bottom on the inside of the generator end stops springs (plate springs, see Figure 1) 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 when following the motion of the buoy, causes variation in the frequency and amplitude of the output current and voltage. To manage this, clusters of WECs has to be interconnected. This is done by means of an underwater substation [20,21]. The substation will also be a source of underwater sound, the characteristics of this will be studied when the substation is deployed and operating. A detailed description of the Lysekil project and the WEC can be found in [4,19].

Figure 1. A conceptual sketch of the Lysekil project Wave Energy Converter (WEC).



3. Hearing in Fish

Hearing sensitivity and capability in marine organisms is very different depending on the taxonomic group and species. This is due to the immense variation in anatomy and physiology that occurs in marine hearing species [14]. Fish can detect sequences of pressure waves that propagate through water in two different ways (hear); with the inner ear which is sensitive to pressure change and with the lateral line which is sensitive to particle displacement. Both the lateral line and inner ear are mechanoreceptory systems [22,23].

3.1. The Inner Ear

In many species of fish the inner ear is the main structure for hearing. Its main structure consists of three semi-circular canals and three otolithic organs (*utricle*, *saccule* and *lagena*), which all contain an otolith (ear stone) [23]. These structures are responsible for both vestibular and auditory senses [24]. The otolith is connected via a membrane to sensory hairs that covers the inside walls of the otolithic organs. When the fish is insonified, the tissues of the fish are set in motion, but due to the density of the otolith it moves asynchronous to the rest of the surrounding tissue. The relative motion of the otolith is detected by the sensory hair cells which send neural signals that to the brain with information about the sound [23,25]. Detailed information about function and morphology of the lateral line and inner ear is found in [23,26].

3.2. The Lateral Line

The lateral line responds to near field water movements produced by a sound or to tiny water movements [26,27], with optimal sensitivity to frequencies around 50 Hz [28]. The lateral line consists of neuromasts that lie underneath the skin in a line from the head to the trunk. The neuromast consist of clusters of sensory hair cells that are sensitive to near field low frequent vibrations. Pores in the skin along this line make it possible for water to displace the neuromast, thus altering the activity in the neurons of sensory cells in the neuromast [22]. This is essential for fish to be able to detect currents, maintain position in schools, capture prey and avoid predators and obstacles [28,29].

3.3. Specialists and Generalists

Concerning hearing in fish the species can be divided into two non-taxonomical group: Species with a linkage between gas filled cavities (swimbladder and air chambers) and the inner ear are defined as hearing *specialists.* Species without this linkage or missing swimbladder are defined as hearing *generalists*. Some species have a linkage between the lateral line, swim bladder and the inner ear [30]. A linkage between these cavities and the inner ear increases the sensitivity to sound pressure. Because of the large density difference between the tissue in the fish and the gas in the swimbladder, the walls of the swimbladder starts to move when insonified.

Through the linkage the swimbladder can redirect acoustic power to the inner ear, which increases the sensitivity to sound pressure and frequency limit of hearing [27,31]. Studies reveal that the generalists have a narrower frequency band of hearing than specialists. Generalist species usually have a frequency band of hearing from tens of Hz to about 1 kHz. They have critical hearing band between

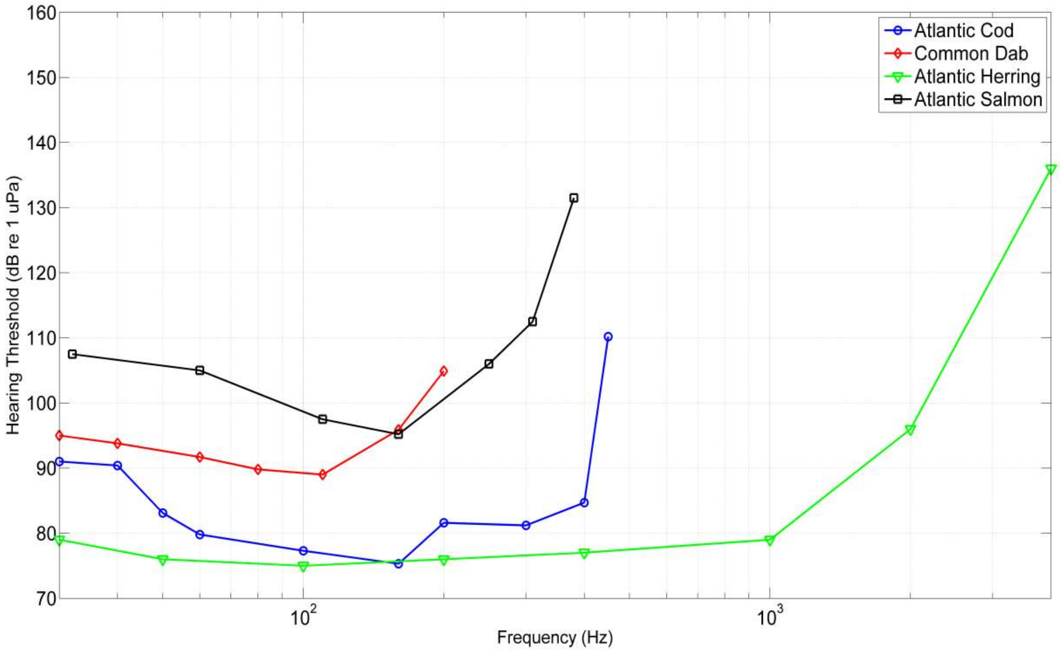
100 and 500 Hz. Specialists have a broader band of hearing frequencies. Their hearing sensitivity is optimal between 100 Hz and 3 kHz, but some species are able to perceive ultrasounds. The cod (*Gadus morhua*) is able to detect frequencies up to 38 kHz [32], and the American shad (*Alosa sapidissima*) and the Gulf menhaden (*Brevoortia patronus*) are able to detect frequencies up to 100 kHz [33,34].

3.4. Hearing Performance

Hearing studies have been carried out on small number of fish species if compared to the total species number (over 32,400 species) [35]. Hearing studies of 53 species are summarized in [14]. These studies have resulted in numerous audiograms that tell what sound pressure levels or particle displacement speed are needed in certain frequencies before there is a reaction (behavioural or physiological) from the fish. In this study only sound pressure levels will be mentioned, since particle displacement has not been measured. The hearing studies that have been performed only covers a few signal types and sound levels, and it is difficult to extrapolate these results to other sounds, but the results provide an indication of what the fish can actually hear. Hearing threshold audiograms of four species of fish that can be found in the Lysekil research site can be found in Figure 2.

There is a great deal of variation in the reported sensitivity of fish to sounds, not only in different species, but also in the same species when thresholds from different studies are compared [14] One of the major reasons for this variation lies in the diverse methods employed in hearing studies of fish, of which the most significant is undoubtedly the acoustic conditions under which the experiments were conducted [36].

Figure 2. Hearing threshold audiograms of four different species that can be found in the *Lysekil Research Site*: Atlantic cod (*Gadus morhua*) [37], common dab (*Limanda limanda*) [38], atlantic herring (*Clupea harengus*) [39] and atlantic salmon (*Salmo salar*) [40].



4. Hearing in Marine Mammals

Marine mammals can be divided in to four different groups; cetaceans (whale, dolphins and porpoises), pinnipeds (seals, sea lions and walruses), sirenians (manatees and dugongs), and three species of fissipeds (the polar bear, and two species of otter). *Cetaceans* can further be divided into mysticetes (11 species of baleen whales) and odontocetes (68 species of toothed whales), cetaceans live their entire lives in water and the hearing is adapted to this. The pinnipeds can be divided into phocids (18 species of true seals) otariids (14 species of eared seals) and *Odobenidae* (one species; walrus). The pinnipeds and the fissipeds spend time in both marine and terrestrial environment, and have adapted their hearing in both water and air. Although there is no information about the underwater hearing capabilities of the polar bear [41]. There is great variation in the range of frequency that these different groups hear and use. Special adaptations are found in all groups, distinctive to their level of adaptation to water and their hearing capabilities [42].

4.1. The Ear

A brief description of marine mammalian ears and hearing capabilities will be reproduced here. For more detailed descriptions see review on marine mammals hearing [42]. The ears of marine mammals consist of the same three basic components that of a terrestrial mammal; an external ear (sound reception), an air filled middle ear with membranes and bony levers (transmits and amplifies acoustic energy) and a fluid filled inner ear with mechanical resonators and sensory cells (filters the signal and converts it into neural impulses that go to the brain) [43].

4.1.1. The External Ear

The outer ear is the external portion of the ear, which consists of the *pinnae*, and external *auditory meatus* (ear canal). It cumulates sound energy and focuses it on the tympanic membrane (eardrum). In most marine mammals the *pinnae* is absent or greatly reduced. The ear canal in cetaceans is very narrow and plugged with cellular debris and wax and it is uncertain if it is used to transmit sound to the middle ear [42]. In odontocetes there are indications that the teeth and lower jaw fats may act as sound conductors to the middle ear [44,45]. How sound reaches the middle ear in mysticetes is less well understood, it might be through soft tissue and bones, or through the narrow ear canal [42]. Phocids have narrow ear canals that can be closed using voluntary muscles, but the condition (air filled, water filled or collapsed) of the ear canal during underwater hearing is not known [46]. Otariids have broader ear canals which are thought to be used to transmit sound to the middle ear both in air and water. No soft tissue paths for underwater sound transmission have been found in seals, but their existence has not been ruled out [42]. The exact sound reception paths in sirenians are not known, but they may use the zygomatic process (a cartilaginous structure in the skull, filled with lipids) found below the eye on both sides to transmit sound to the middle ear. Very little is known of the underwater hearing capabilities of the marine Fissipeds. Both the polar bear and otters have well defined *pinnae*. In otters it has been suggested [47] that *pinnae* folds down over the ear canal during dives. This could close the ear and prevent the ear canal from getting water filled. The *pinnae* of polar bear is similar to those of other ursids (bears), but since polar bears dive in cold waters special adaptations to close the ear canal might exist.

4.1.2. The Middle Ear

The middle ear is the portion of the ear internal to the tympanic membrane (eardrum), to the external of the oval window of the cochlea. The basic components of the middle ear are the same in all mammals; the *cavum tympani* (tympanic cavity) and the three *ossicles* (*Malleus*, *Incus* and *Stapes*). The *ossicles* are the bones which couple vibration of the eardrum to the fluid and membranes of the inner ear. These bones differ from group to group and also between species within the same group. The *ossicles* of the cetaceans are large and dense, and vary in size, shape and stiffness [42,48]. In odontocetes the *ossciles* are stiffly jointed, and in mysticetes they are more loosely jointed. Stiffness in this chain allows for efficient transmission of high frequency sound (needed for ultrasonic echolocation in odontocetes), and a more pliable chain allows a more efficient transmission of low frequency sound [42]. The *ossicles* in pinnipeds are diverse, otariids have *ossicles* that resemble terrestrial mammals, phocids have more massive *ossicles* and they vary in shape with species [48]. The sirenians have large mass dense and loosely jointed *ossicles*. The shape of Stapes is columnar, a shape found in reptiles rather than mammals. The middle ear of the marine fissipeds are similar to terrestrial mammals of the same size [42].

4.1.3. The Inner Ear

An inner ear is found in all vertebrates, with variations in form and function. In mammals the inner ear has one part dedicated to balance; the vestibular system, and one part dedicated to hearing; the cochlea. The cochlea is a hydro mechanical frequency analyser. It converts sound pressure impulses into electrical impulses which are passed on to the brain via the auditory nerve [49]. The cochlea is a fluid-filled spiral structure that is larger at the base and narrower at the apex. Inside the cochlea the basilar membrane is found, and on it the organ of Corti (sense organ of hearing) is found. Upon delivery of an acoustic signal into the fluid-filled cochlea via the oval window, the basilar membrane undergoes an oscillatory motion at the frequency of the sound, resulting in a wave travelling toward its distal end. Cilia in the sensory hair cells in the organ of Corti are stimulated mechanically by this motion and converts the stimulation to it electrical signals through the release of neurotransmitters. The neural signal goes to the brain with information of the sound (timing, frequency, amplitude and phase) [49–51].

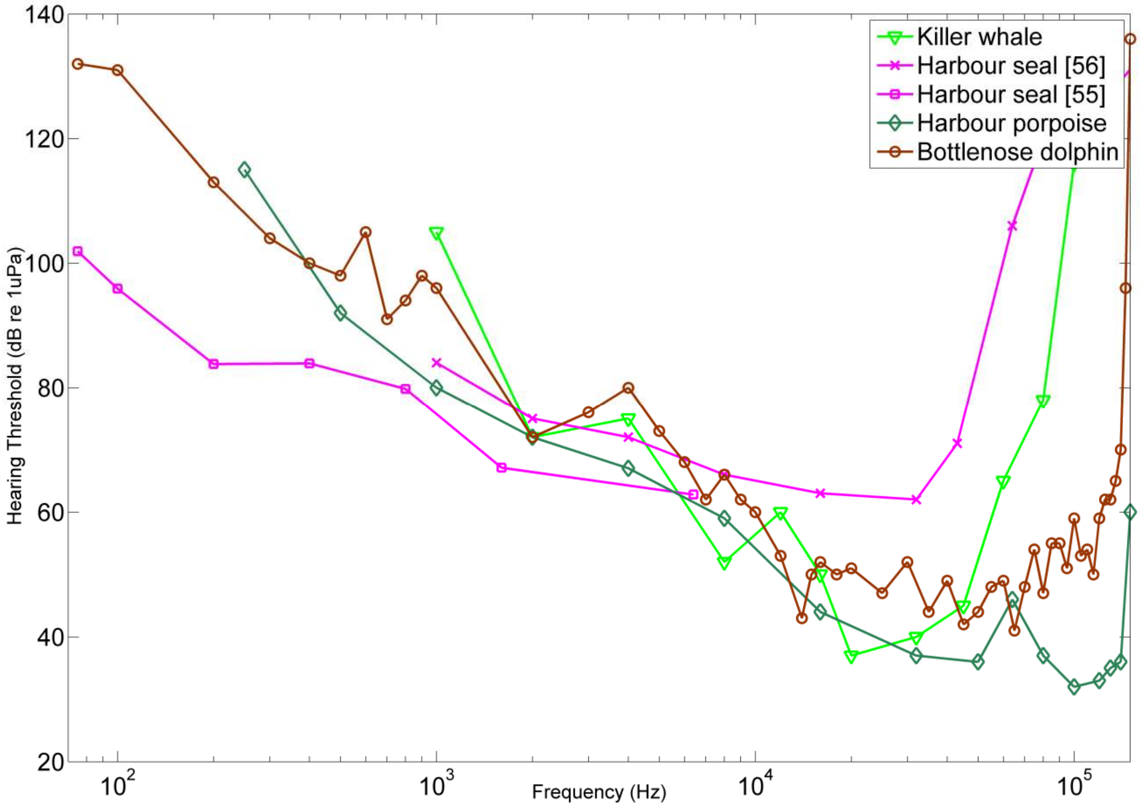
The basilar membrane varies in thickness, stiffness and width along its length, near the base (near the oval window) it is thick and narrow (stiff) and at the apex it is thinner and wider (more flexible). A thicker and stiffer basilar membrane is more tuned to high frequencies, and a thinner and more flexible is more tuned to low frequencies [52]. Odontocetes have adaptations (a narrow, thick and stiff basilar membrane) in their inner ear that correlate to ultrasonic hearing (frequencies > 20 kHz). The basilar membrane of mysticetes is broad, thin and elastic, which indicate that they may have good infrasonic hearing [42]. The inner ears of pinnipeds have been sparsely studied. It seems that they are similar to terrestrial hearing generalists and no obvious adaptations to either high ultra or infra sounds have been found. There are indications that larger species have some adaptations to low frequency hearing [42].

Sirenians have a mixture of terrestrial and marine mammal features. The basilar membrane and neural distribution is similar to pinnipeds, and no specializations related to ultra or infra sound have been found [48,53]. Little data is available on marine fissipeds but they seem to have similar inner ear as terrestrial mammals in the same size, and like pinnipeds they lack obvious specializations [42].

4.2. Hearing Performance

There are models that predict "in air" hearing abilities in terrestrial mammals from anatomical information [40]. There are no such models for in water hearing abilities in marine mammals, it has to be directly measured. Hearing studies have been carried out on a number of marine mammals. Studies of 23 species are summarized in a report [14]. These studies have resulted in numerous audiograms that tell what sound pressure levels are needed at certain frequencies before there is a reaction (often behavioural) from the animal. Most of the studies were done on a small number of animals and thus knowledge about infraspecific variation in hearing abilities is relatively poor. Audiograms of four different marine mammal species are found in Figure 3.

Figure 3. Hearing threshold audiograms of four different marine mammals, of which two (*P. vitulina* and *P. phocoena*) can be found in the *Lysekil Research Site:* killer whale (*Orcinus orca*) [54], harbour seal (*Phoca vitulina*), here two different studies are shown to cover more studied threshold frequencies [55,56], harbour porpoise (*Phocoena phocoena*) [57] and bottlenose dolphin (*Tursiops truncatus*) [58].



4.3. Produced Sound

4.3.1. Marine Mammals

Most marine mammals are known to produce different sounds under water. Many of these sounds may be for communication and others are for echolocation (for feeding or navigation). Odontocetes are known to communicate at frequencies between 100 Hz and 35 kHz [42], but some species such as spotted dolphin (*Stenella attenuate*), harbour porpoise (*Phocoena phocoena*) and bottlenose dolphin (*Tursiops truncates*) use echolocation sounds up to 130–170 kHz. [59]. Mysticetes lack the ability to echolocate with high frequency sounds and are known to communicate at frequencies between 10 Hz and 28 kHz, but most produced sounds lie between 10 Hz and 4 kHz. Pinnipeds are known to vocalise between 20 Hz and 10 kHz, but there are species that produce ultrasonic sounds (*Halichoerus grypus*: 150 kHz, *Hydrurga leptonyx*: 164 kHz and *Phoca vitulina*: 150 kHz). The sirenians are known to produce sounds between 500 Hz and 18 kHz [60].

4.3.2. Fish

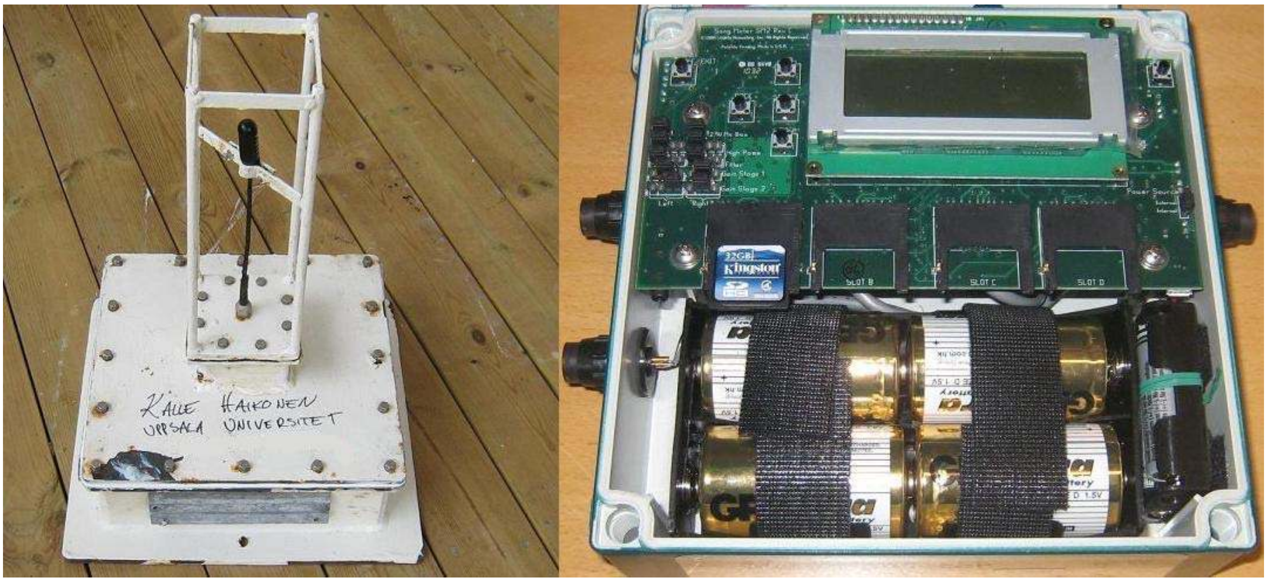
Fish are also known to produce different sounds under water, however they may not be as vocal as marine mammals. In teleost fish many sounds are produced by movement of bones or contraction of special sonic muscles coupled to the swimbladder [61]. Many of these sounds are >1000 Hz but there are exceptions. The Atlantic cod (*Gadus morhua*) can produce low frequent clicks (5–10 Hz) [62] and grunts between 50 and 500 Hz, lasting up to 1 s. [63]. The Atlantic herring (*Clupea harengus*) is known to produce pulse chirps between 3 and 4.1 kHz [64], and the Pacific herring (*Clupea pallasii*) can produce pulse sounds from 1.7 Hz up to at least 22 kHz [65].

5. Materials and Method

5.1. Field Sampling

Measurements of operational noise were performed during a period of 39 days, between 19 April and 28 May in 2011. A submersible passive recording device was descended to the seabed in the wave power site at a depth of approx. 25 m. During the measuring period there were two operating WECs in the area. The recording device consisted of a recorder and a hydrophone. The data recorder was a Song Meter 2 (SM2) platform (Wildlife Acoustics Inc., Concord, MA, USA) with a sampling rate of 44.1 kHz and 16-bit recording technology. The hydrophone was a HTI 96-Min (High Tech Inc, Long Beach, MS, USA) which had a sensitivity of −165 dB re: 1 V/µPa and a flat frequency response range between 2 Hz and 30 kHz. A gain of +24 dB was set in the data recorder, which resulted in a system sensitivity of −141 dB re 1 µPa. The recording device was calibrated by the supplier before the measurements. An error in ±1 dB is estimated to occur in the SM2 digital conversion process. An underwater housing was made for the SM2 platform and the hydrophone was suspended outside of the underwater housing (Figure 4).

Figure 4. To the left is the underwater housing for the data recorder, the hydrophone is suspended 40 cm above the surface on which it is deployed. To the right is the data recorder (SM2).

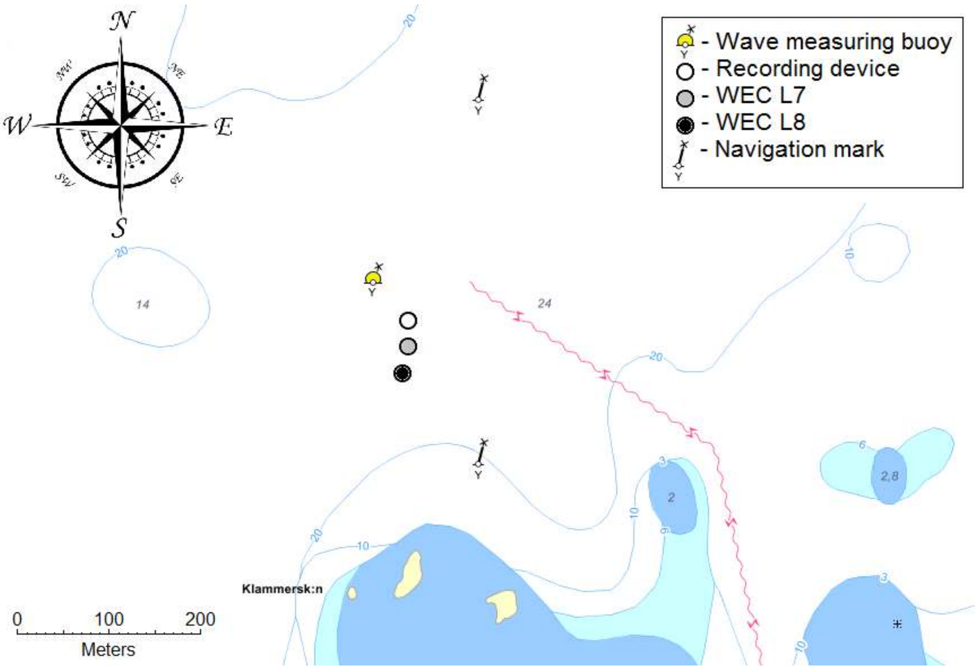


The SM2 platform was programmed to record 5 min in the beginning of every 30 min between 19 April and 28 May in 2011. The digitized sound was stored in WAC-lossless format then converted to WAV format. Acoustical analysis was performed in SpectraPlus 5.0 (Pioneer Hill Software), Songscope 4.0.6 (Wildlife Acoustics Inc.) and Matlab R2009a (Mathworks Inc., Natick, MA, USA).

The recorder was deployed approximately 20 m from the nearest WEC and the other WEC was approximately 40 m away from the recorder. All measurements were performed from this position. At the wave power site there was a wave measuring buoy (Waverider Fl) from Datawell BV Oceanographic Instruments (Haarlem, the Netherlands) approx. 60 m from the recording device. The wave measuring buoy continuously measured the wave height, and the Significant Wave Height (SWH) was calculated for every half hour in the area of interest. The locations of the hydrophone, WECs and wave measuring buoy can be seen in Figure 5.

The wave power site (*The Lysekil Research Site*) where the measurements were performed is located at the Swedish west coast 10 km south of the city Lysekil and 2 km offshore. There is a sea-lane for recreational boats 2 km east from the research site. This might give an extensive contribution to ambient noise during the recreational boating season (Jun-Oct). The area of the test site is 0.4 km^2 and is situated with at 58°11’44.12’’, 11°22’22.50’’ (WGS84, DMS). The mean wave height in the area is approximately 1.5 m, and the mean wave period is approximately 5 s [66]. The depth in the area ranges between 24 and 26 m, and the bottom is soft bottom consisting of silt and sand [67].

Figure 5. Map of the placement of generators and measuring equipment in the *Lysekil Research Site*.



5.2. Acoustical Analysis

The sounds from the WECs were categorized depending of the wave state. The significant wave height varied from 0.1 to 3.5 m during the sampling period. Measurements when the significant wave height was >0.5 m were excluded in this study due to the presence of high levels of overload distortion. Spectrograms and frequency analyses were done in wave states of 0.50 m of SWH. The background sound levels (ambient noise) were also analysed in the same manner as the sound from the WECs, during this wave state. The frequency analysis was performed with FFT (Fast Fourier Transform), with a FFT sample size of 16,384 and a Hanning window with 75% smoothing. This gave a spectral line resolution of 2.692 Hz and a time resolution of 0.093 s. This setup was chosen to get high frequency resolution to be able to detect narrow frequency peaks. The amplitudes were given in dB re 1 μPa. The frequency analysis was made in a frequency band between 40 and 22,000 Hz. Source level (SL) was roughly estimated by calculating the transmission loss (TL) using the equation for practical spreading law:

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

where R is the distance to the sound source and the factor 15 represents an intermediate spreading condition between spherical spreading (a factor of 20) and cylindrical spreading (a factor of 10) [59,68].

6. Results

The measurements showed that the main sound emitted from the WECs was a transient/pulse noise (short duration and high amplitude). The pulse originates from when the translator hits the end stop springs (upper or lower). The pulses often came in series of two or more. The first pulse derives from when the plate spring (end stop) is hit by the translator, and the second occurs when the plate spring elongates if it has been depressed enough. Additional pulses with lower energy sometimes followed the two initial pulses, this as a result of the translator bouncing on the end stop (only observed in 0.5 m of SWH). The rise time (time required for the signal to reach full power) is instant and the duration of one pulse is approximately 0.2–0.3 s, peak time is approximately 0.05–0.1 s. A large portion of the recordings (95% of everything >0.5 m of SWH) were corrupted due to overload distortion when the sound pressure level peak to peak ($SPL_{p\text{-}p}$) of the sound exceeded the sensitivity of the measuring equipment. This limits measurements in this study to pulses that have $SPL_{p\text{-}p} \leq 141$ dB *re* 1 µPa. The amplitudes in all charts are relative to maximum signal level: 141 dB re 1 uPa. When overloaded the signal was clipped and this gave distortion covering the entire spectrum (Figures 6 and 7), but that was clearly noticeable in frequencies above 1 kHz (Figure 8).

Figure 6. Spectrogram of the noise from an operating WEC. It can be seen that the pulses come in series of two or more, three different events shown here: first a double pulse, then a quadruple pulse and last a triple pulse. Most of the energy is in frequencies below 1 kHz with peak frequency at 145 Hz. Time on the *x*-axis and frequency on the *y*-axis. Signals that clearly cover the entire spectrum (marked with red arrows) are clipped (distorted) due to system overload.

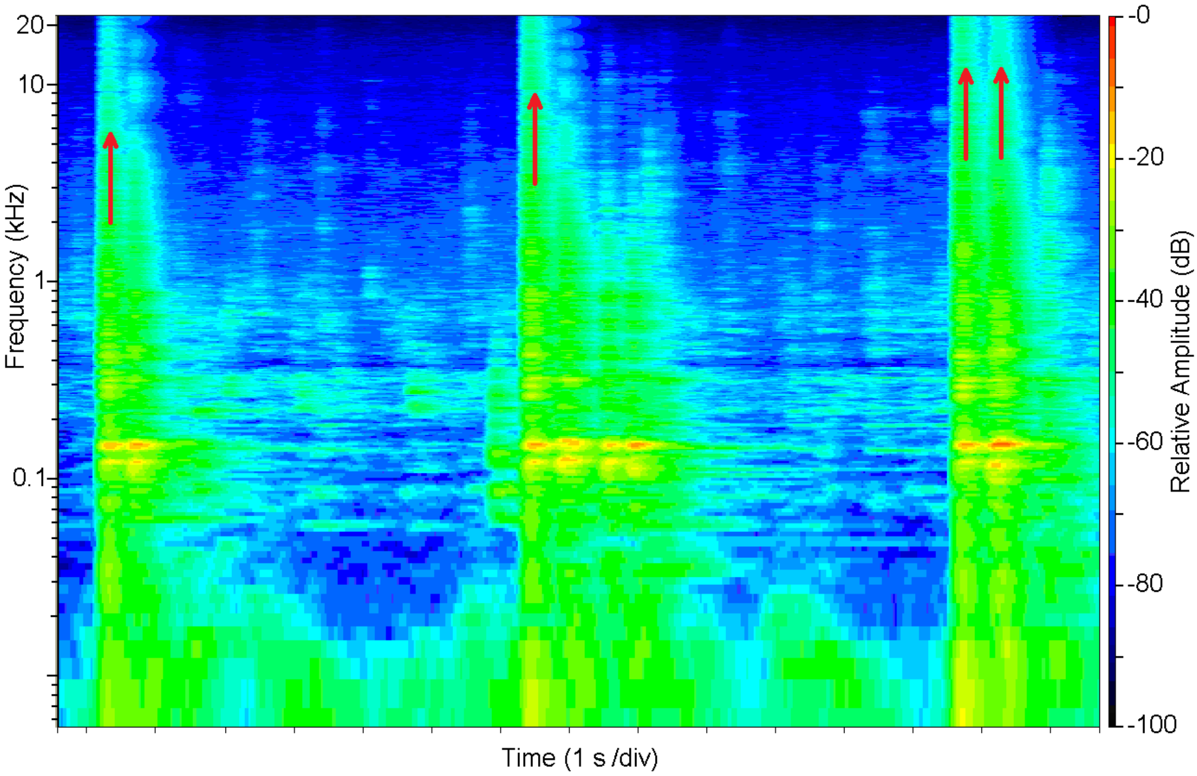


Figure 7. The logarithmic value of the linear amplitude value for each sampling point from the wave form data shows amplitude change over time in 0.5 m SWH (same time period as in Figure 1). Time (s) on the *x*-axis and relative amplitude (dB) on the *y*-axis. Clipped (distorted) signals are marked with red arrows.

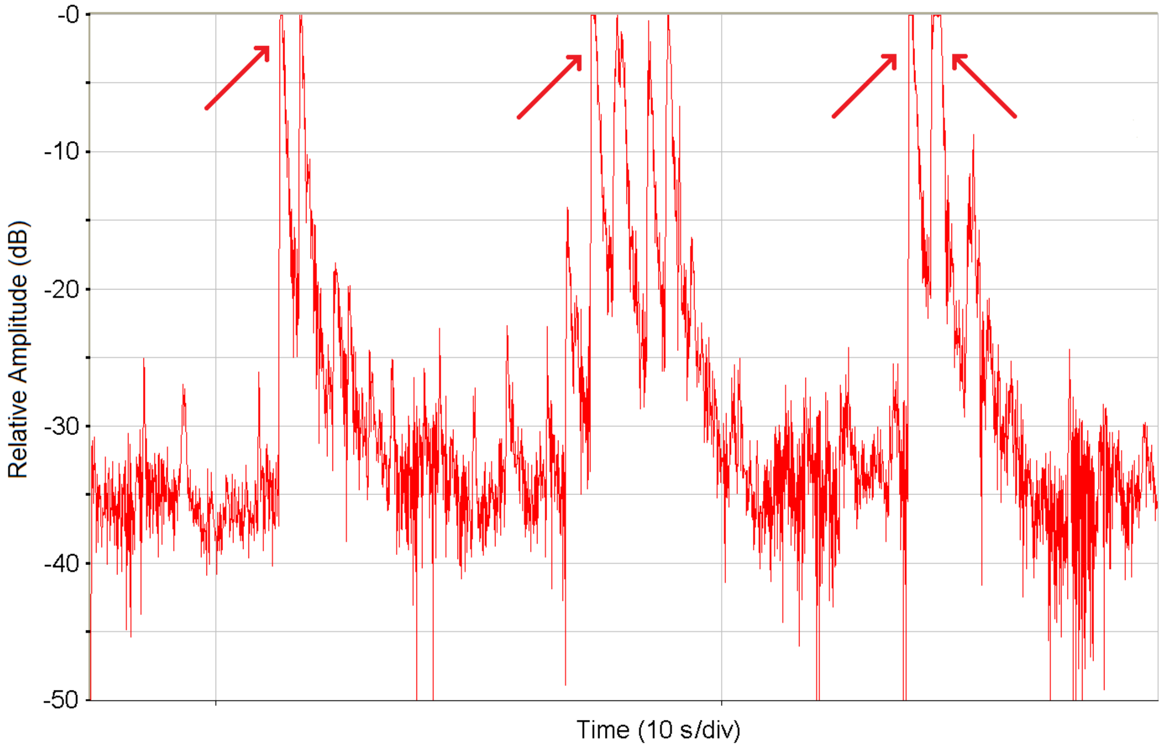
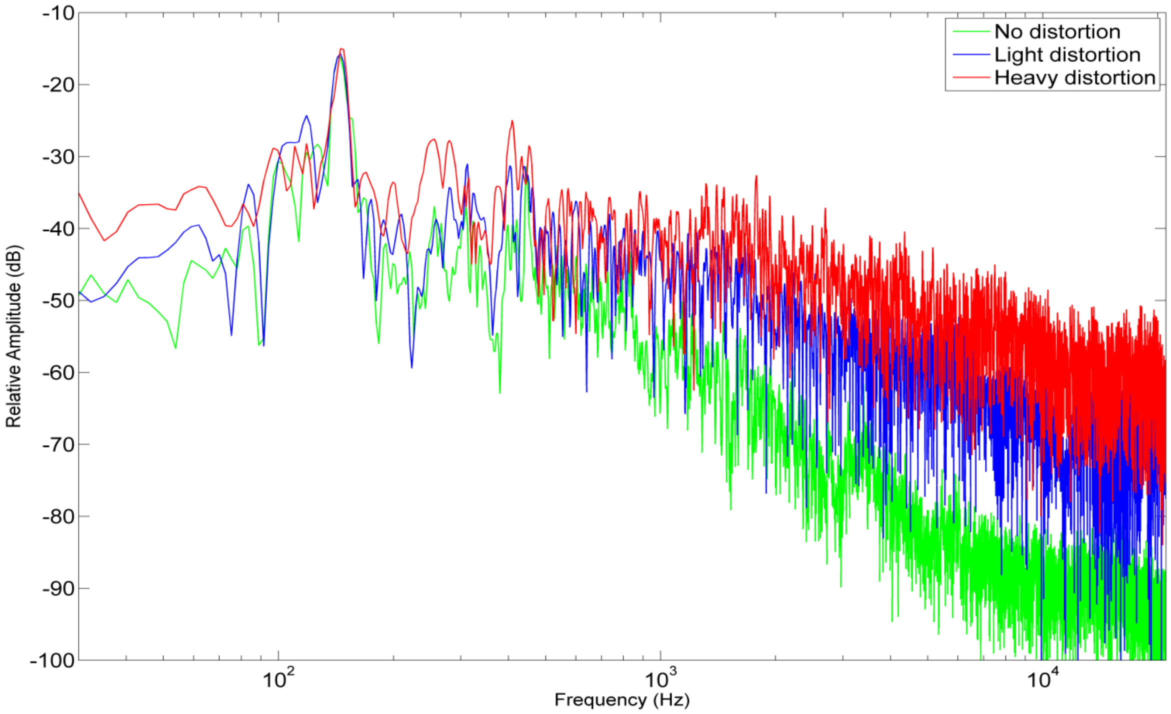


Figure 8. Three signals with different levels of distortion. The *x*-axis represents the frequency (Hz) and the *y*-axis represents relative amplitude (dB).



All further analysed signals in this paper are undistorted from 0.5 m SWH. Fast Fourier Transform (FFT) analysis was performed on both single pulses (SP) and double pulses (DP). Spectrums from SPs and DPs are shown in Figure 9a,b. The sound pressure level root mean square (SPL_{rms}) for the entire sound was calculated for every analysed SP or DP. Max and mean values are shown in Table 1. The FFT analysis gave an average value and a peak value spectrum for each analyzed pulse (Figure 10a). The noise from the WECs was detectable above the ambient noise levels over all frequencies (Figure 10b). Most of the energy in the pulse is below 1 kHz, with peak amplitudes at 118, 145, 310, 412 and 447 Hz. The frequency with the highest amplitude is 145 Hz. Maximum undistorted level at 145 Hz in was measured to 126 dB re 1 µPa, average level (n = 50) at 145 Hz was 121 dB re 1 µPa (Table 1). It was discovered that the WEC closest (20 m away) to the recording device was incorrectly assembled. This resulted in end stop hits already at 0.5 m SWH. The other WEC (40 m away) did not have any end stop hits until 2.0 m p-p waves passed. Thus all WEC noise measurements are from a distance of 20 m.

Figure 9. (**a**) Spectrums of single pulses in 0.5 m of SWH. Each green line represents one pulse (N = 50), the red line represents the average of all green lines; (**b**) Spectrum of double pulses in 0.5 m of SWH. Each green line represents one pulse (N = 50), the red line represents the average of these lines. Frequency on the x-axis and amplitude on the y-axis.

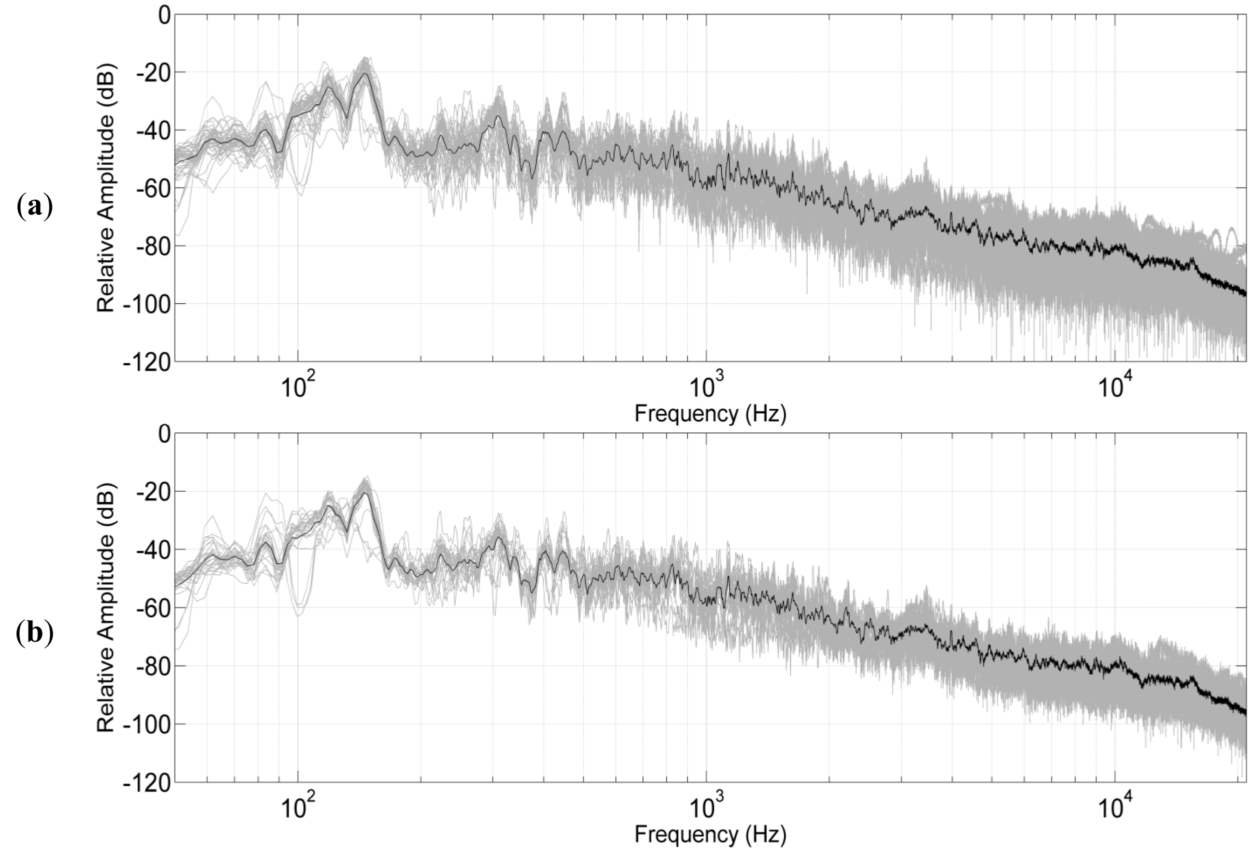


Figure 10. (**a**) Comparison between spectrums of single and double pulses. The single pulse line is the average line of $N = 50$ and double pulse line is the average of $N = 30$; (**b**) Comparison between ambient noise. The single pulse line is the average line of $N = 50$ and ambient noise line is the average of $N = 30$. Frequency on the x-axis and amplitude on the y-axis.

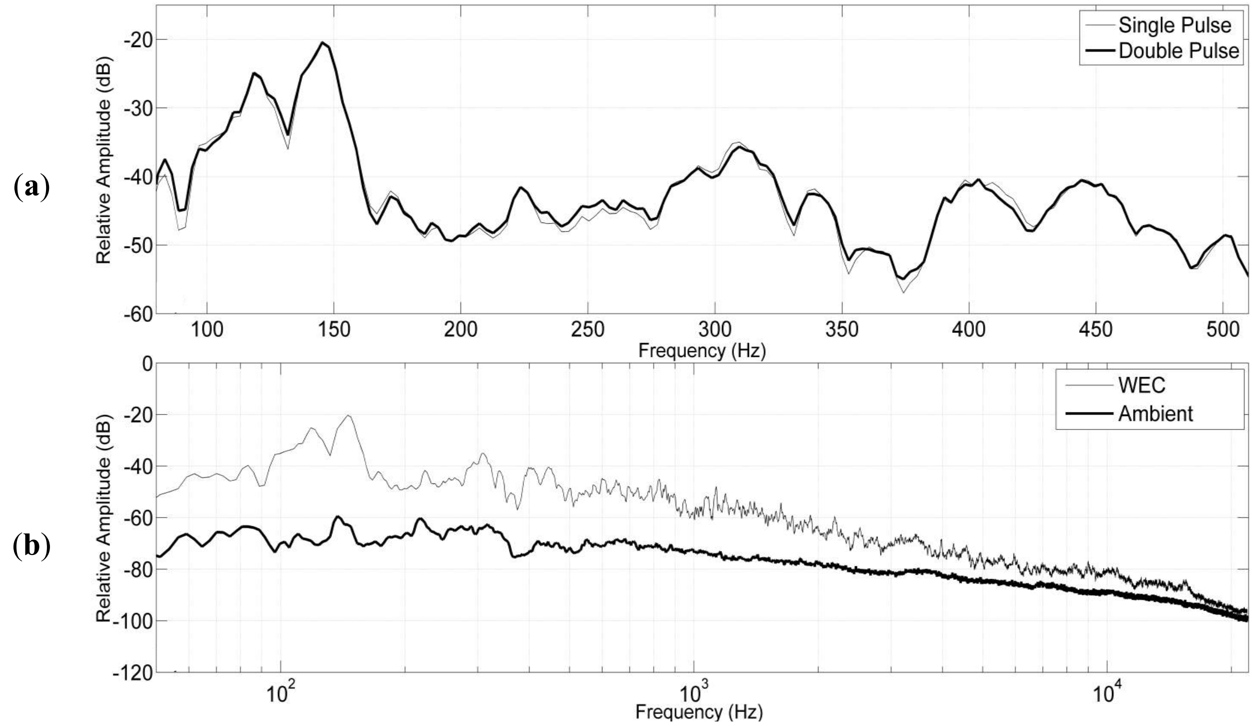


Table 1. Summary of WEC and ambient noise measurements. Shown are number of samples (N), sound duration, Sound Pressure Level Root Mean Square (SPL_{rms}) at 145 Hz, the entire sound and estimated Source Level. Ambient noise was measured in the presence of inactive WECs (WECs without buoys). All sounds are from measurements in 0.5 m SWH.

Spectrum type	**N**	**Duration (s)**	**145 Hz (dB 1 μPa$_{rms}$) Max/Mean**	**Total (dB 1 μPa$_{rms}$) Max/Mean**	**Estimated SL (dB 1 μPa$_{rms}$) Max/Mean**
Single Pulse	50	0.2–0.3	126/121	133/129	153/149
Double Pulse	30	0.5–0.6	126/121	131/129	151/149
Ambient Noise	50	0.3	91/78	107/101	-/-

The peak frequencies (118, 145, 310, 412 and 447 Hz) in single pulse and double pulse were compared statistically with non-parametric test (Wilcoxon Signed Rank test, $N = 30$). A significant difference was only found at 412 Hz ($p = 0.001$), with slightly higher values in single pulse. At the other frequencies $p > 0.05$. This means that the second pulse does not generally alter the overall spectrum significantly. The difference in this frequency is so small that it is negligible when comparing to audiograms due to natural variation. A comparison between single and double pulse spectrums is found in Figure 10a. Spectra of the noise from the WECs and ambient noise measurements are shown in Figure 10b. The SPL_{rms} was lower for double pulses; this is due to the lower energy in the second pulse. The number of pulses was counted for each measuring period and there was an indication of a higher rate of end stop hits during high water level (above normal level) compared to low water level (below normal level). High water level measurements had a mean of 43 end stop hits and low water measurements had a mean of 35 end stop hits.

7. Conclusions

Much of the measurements in this study were corrupted by overload distortion. This makes it impossible to decide the upper limit for the noise amplitude. It also eliminated the possibility of comparing the noise in different wave states since there was increasing distortion with increasing wave height. An assembly error in one of the WECs resulted in that the translator hit the end stop springs already in 0.5 m of SWH. End stop hits should not occur until waves <2.0 m p-p passes the surface buoy. The frequency range of which the translator hit the end stop varied considerably (4–84 hits per five min), with the highest frequency at high water level. This indicated that the line connecting the point absorbing buoy to the generator was too short. The measured noise is not representative for the operational sound of a WEC in 0.5 m of SWH, since there should not be any end stop hits in this wave state. The noise is more likely to represent the noise levels at wave state around 1.8–2.0 m of SWH, where waves >2.0 m p-p are frequent.

In the analysed design of WEC the main operational noise derives from when translator hits the end stop springs. The noise is a transient/pulse (short duration and high amplitude) noise with most its energy in frequencies <1000 Hz. In the analysed pulses (undistorted pulses in 0.5 m of SWH) peak amplitude was found at 145 Hz with an average value of 126 dB *re* 1 μPa. The SPL_{rms} for an entire pulse sound at 20 m from a WEC was 133 dB re 1 μPa (max value) and 129 dB re 1 μPa (average value). Comparing with the threshold audiograms in this study it is clear that all analysed species will be able to hear this noise at a distance of 20 m away from the WEC in the measured ambient noise levels. The noise intensity at this distance is higher than the hearing thresholds for all fish species at frequencies between 100 and 200 Hz, where the peak frequency (145 Hz) was between ~15–45 dB over the hearing thresholds (15 dB for the least sensitive and 45 dB for the most sensitive species). These levels are not predicted to induce any behavioural reactions in the least sensitive fish [69]. Furthermore the intensity of the analysed noise is most probably below the threshold of causing physical injury to fish [15].

The marine mammals analysed in this study are more sensitive to frequencies >1000 Hz. Comparing spectrum levels of WEC noise and hearing threshold audiograms of the mentioned marine mammals, one can see that only one species (Harbour seal) is able to hear the peak frequency (145 Hz). Most of the energy in the WEC noise is in frequencies below the frequency hearing range of the other species. The noise barely exceeds the hearing threshold (0–10 dB) in frequencies between 500 and 10,000 Hz in killer whale, bottlenose dolphin and harbour porpoise. However the spectrum in this study has high frequency resolution, and when comparing spectrums with audiograms, broadband levels should be applied. 1/3rd octave bands should be used in these comparisons [70]. Doing so will increase the spectrum levels. This has not been done in this study. However assuming an increase in spectrum levels it can be expected that the WEC noise will be audible for all analysed marine mammals.

When estimating whether if the noise is disturbing or not is truly difficult. The threshold for behavioural disturbance (peak to peak broadband noise level) is: 140 dB re 1 μPa for bottlenose dolphin, 90 dB re 1 μPa for harbour porpoise and 160 dB re 1 μPa for Harbour seal [71]. This indicates that even though harbour porpoise and bottlenose dolphin have less sensitive hearing than Harbour seal, they are more sensitive to noise, so comparing with an audiogram does not reveal the whole truth. Predictions are that at 20 m in the analyzed wave from a WEC there could be a behavioural reaction from harbour porpoise and bottlenose dolphin, but it is unlikely that there will be any reaction from the harbour seal. Masking effects on any of the marine mammals in this study is unlikely: The dominant sound production frequencies range in killer whale, bottlenose, Harbour porpoise and Harbour seal ranges between 0.3 and 142 kHz with source levels between 125 and 225 dB re 1 μPa [59]. At a distance of 150 m the SPL_{rms} of the total noise will have decreased with 32 dB (using Equation 1), reaching the measured ambient noise levels (Table 1). A preliminary estimation is that the risks of injury to any of the analysed the marine mammals due to short time exposure to the analysed WEC noise in are unlikely.

The upper limits in amplitude of the WEC noise are not known. It is safe to assume that the intensity of the pulses will increase with increasing wave height. One indication of this is the increasing overload distortion with increasing wave height. Basically nothing is known about the effect on marine organisms from the noise from WEC of this design. Is a cumulative effect from being exposed to multiple pulses from a WEC (which can come as frequently as two pulses per six s) or not? If this is the case, multiple pulses that are harmless by themselves, might add up and cause hearing loss, tissue damage or even death. At this time nothing is known about such effects from WEC noise. WECs should be designed to emit as little noise as possible, this to have as little impact on its surrounding environment as possible. In the WEC design analysed in study (with plate springs), there was much metal to metal contact when the translator hit the end stop, this event was responsible for the main noise. The measurements and conclusions in this have led to alterations in future WEC design.

More studies on underwater noise are needed. Both studies which identify and quantify sounds in the oceans and studies that examine if these sounds have any significant impact on marine organisms. One can expect that different WEC designs will emit different kinds of noise. The characterisation of the main noise of an operating WEC can lead to alterations in the design, as in the *Lysekil project*. Studies that examine how the noise affects marine organisms are also important. Will there be any masking effects, behavioural reactions and or physical injuries? And will there be accumulative effects from noise that is harmless in short time exposure?

Acknowledgments

We thank the Swedish Energy Agency (STEM), Vattenfall AB, the Gothenburg Energy Research Foundation, Draka Cable, the Göran Gustavsson Research Foundation, Vargöns Research Foundation, Falkenberg Energy AB and the Wallenius Foundation for supporting the experiments at the Lysekil research site; and Statkraft AS for funding this study.

Thanks to Sherwood Snyder at Wildlife Acoustics and John Patte at Pioneer Hill Software for comments and feedback; Ulf Ring, Thomas Götschl at the department of electricity at Uppsala university, for help with practical issues; Mats Virtanen, Niklas Persson and Erik Leijerskog for help in the field. A special thanks to Erik Peterson at for constructive criticism and comments to earlier drafts of this article. This study was funded by Statkraft, Norway.

References

1. Caracas, M.C. The OPD Pelamis WEC: Current status and onward programme (2002). *Int. J. Ambient Energy* **2003**, *24*, 21–28.
2. Polinder, H.; Damen, M.E.C.; Gardner, F. Linear PM generator system for wave energy conversion in the AWS. *IEEE Trans. Energy Convers.* **2004**, *20*, 583–589.
3. Kofoed, J.P.; Frigaars, P.; Friis-Madsen, E.; Sørensen, H.C. Prototype testing of the wave energy converter Wave Drageon. *Renew. Energy* **2006**, *31*, 181–189.
4. Waters, R.; Stålberg, M.; Danielsson, O.; Svensson, O.; Gustafsson, S.; Strömstedt, E.; Eriksson, M.; Sundberg, J.; Leijon, M. Experimental results from sea trials of an offshore wave energy system. *Appl. Phys. Lett.* **2007**, *90*, 034105:1–034105:3.
5. Langhamer, O.; Wilhelmsson, D.; Engström, J. Artificial reef effect and fouling on offshore wave power. *Eustarine Coast. Shelf Sci.* **2009**, *82*, 426–432.
6. Langhamer, O.; Wilhelmsson, D. Colonisation of fish and crabs of wave energy foundations and the effects of manufactured holes—A field experiment. *Mar. Environ. Res.* **2009**, *68*, 151–157.
7. Johnson, T.D.; Barnett, A.M.; DeMartini, E.E.; Craft, L.L.; Ambrose, R.F.; Purcell, L.J. Fish production and habitat utilization on a southern California artificial reef. *Bull. Mar. Sci.* **1994**, *55*, 709–723.
8. Lozano-Alvarez, E.; Briones-Fourzán, P.; Negrete-Soto, F. An evaluation of concrete block structures as shelter for juvenile Caribbean spiny lobsters, *Panulirus argus*. *Bull. Mar. Sci.* **1994**, *55*, 351–362.
9. Gosling, L.M.; Sutherland, W.J. *Behaviour and Conservation*; Cambridge University Press: New York, NY, USA, 2004; p. 252.
10. Hildebrand, J.A. Anthropogenic and natural sources of ambient noise in the ocean. *Mar. Ecol. Progr. Ser.* **2009**, *395*, 5–20.
11. Southall, B.L.; Bowles, A.; Ellison, W.T.; Finneran, J.J.; Gentry, R.L.; Greene, C.R.; Kastak, D.; Ketten, D.R.; Miller, J.H.; Nachtigall, P.E.; *et al.* Marine mammal noise exposure criteria: Initial scientific recommendations. *Aquat. Mamm.* **2007**, *33*, 411–521.
12. Hastings, M.C. Coming to terms with the effects of ocean noise on marine animals. *Acoust. Today* **2008**, *4*, 22–34.
13. Popper, A.N.; Hastings, M.C. The effects of anthropogenic sources of sound on fishes. *J. Fish Biol.* **2009**, *75*, 455–489.
14. Nedwell, J.R.; Edwards, B.; Turnpenny, A.W.H. Fish and Marine Mammals Audiogram: A Summary of Available Information. Available online: http://www.subacoustech.com/wp-content/uploads/534R0214.pdf (accessed on 16 May 2013).
15. Abbott, R.; Bing-Sawyer, E. Assessment of Pile Driving Impacts on the Sacramento Blackfish (*Orthodon microlepidotus*). In *Draft Report Prepared for Caltrans District 4*; CalTrans: San Francisco, CA, USA, 2002.
16. Wahlberg, M.; Westerberg, H. Hearing in fish and their reactions to sounds from offshore wind farms. *Mar. Ecol. Progr. Ser.* **2005**, *288*, 295–309.
17. Nedwell, J.R.; Turnpenny, A.W.H.; Lovell, J.M.; Edwards, B. An investigation into the effects of underwater piling noise on salmonids. *J. Acoust. Soc. Am.* **2006**, *120*, 2550–2554.

18. Ruggerone, G.T.; Goodman, S.; Miner, R. *Behavioural Response and Survival of Juvenile Coho Salmon Exposed to Pile Driving Sounds*; Report for the Port of Seattle; NRC: Seattle, WA, USA, 2008.
19. Leijon, M.; Boström, C.; Danielsson, O.; Gustafsson, S.; Haikonen, K.; Langhamer, O.; Strömstedt, E.; Stålberg, M.; Sundberg, J.; Svensson, O.; *et al.* Wave energy from the north sea: Experiences from the Lysekil research site. *Surv. Geophys.* **2004**, *29*, 221–240.
20. Thorburn, K.; Bernhoff, H.; Leijon, M. Wave energy transmission system concepts for linear generator arrays. *Ocean Eng.* **2004**, *31*, 1339–1349.
21. Rahm, M.; Boström, C.; Svensson, O.; Grabbe, M.; Bülow, F.; Leijon, M. Offshore underwater substation for wave energy converter arrays. *Renew. Power Gener.* **2010**, *4*, 602–612.
22. Helfman, G.S.; Collette, B.B.; Facey, D.E. *The Diversity of Fishes*; Wiley-Blackwell: Hoboken, NJ, USA, 1997.
23. Popper, A.N.; Fay, R.R. The Auditory Periphery in Fishes. In *Comparative Hearing: Fish and Amphibians*; Springer Handbook of Auditory Research; Springer: New York, NY, USA, 1999; Volume 11, pp. 43–100.
24. Popper, A.N.; Coombs, S. Auditory mechanisms in teleost fishes. *Am. Sci.* **1980**, *68*, 429–440.
25. Pumphrey, R.J. Hearing. In *Symposia of the Society for Experimental Biology*; Academic Press: New York, NY, USA, 1950; Volume 4, pp. 3–18.
26. Hawkins, A.D. Underwater Sound and Fish Behaviour. *Behaviour of Teleost Fishes*; Pitcher, T.J., Ed.; Croom Helm Ltd.: Beckenham, UK, 1986; pp. 114–151.
27. Bleckmann, H. Role of the Lateral Line in Fish Behaviour. In *The Behaviour of Teleost Fishes*; Pitcher, T.J., Ed.; Springer: Berlin, Germany, 1986; pp. 114–151.
28. Sand, O.; Enger, P.S. Evidence for an auditory function of the swimbladder in the cod. *J. Exp. Biol.* **1973**, *59*, 405–414.
29. Popper, A.N.; Platt, C. Inner Ear and Lateral Line. In *Physiology of Fishes*; Evans, D.H., Ed.; CRC Press: Boca Raton, FL, USA, 1993.
30. Popper, A.N.; Fay, R.R. Sound detection and processing by fish: Critical review and major research questions. *Brain Behav. Evol.* **1993**, *41*, 14–38.
31. Ladich, F.; Popper, A.N. Parallel Evolution in Fish Hearing Organs. In *Evolution of the Vertebrate Auditory System*; Manley, G., Popper, A.N., Fay, R.R., Eds.; Springer-Verlag: New York, NY, USA, 2004; pp. 95–127.
32. Astrup, J.; Møhl, B. Detection of intense ultrasound by the cod (*Gadus morhua*). *J. Exp. Biol.* **1993**, *182*, 71–80.
33. Mann, D.A.; Lu, Z.; Hastings, M.C.; Popper, A.N. Detection of ultrasonic tones and simulated dolphin echolocation clicks by a teleost fish, the American shad (*Alosa sapidissima*). *J. Acoust. Soc. Am.* **1998**, *104*, 562–568.
34. Mann, D.A.; Higgs, D.; Tavolga, W.N.; Souza, M.; Popper, A.N. Ultrasound detection by clupeiform fish. *J. Acoust. Soc. Am.* **2001**, *109*, 3048–3054.
35. "FishBase" World Wide Web Electronic Publication. Available online: http://www.fishbase.org (accessed on 31 January 2013).
36. Chapman, C.J. Field studies of hearing in teleost fish. *Helgol. Meersunters* **1973**, *24*, 371–390.

37. Chapman, C.J.; Hawkins, A.D. A field study of hearing in the Cod, *Gadus Morhua* L. *J. Comp. Physiol.* **1973**, *85*, 47–167.
38. Hawkins, A.D.; Myrberg, A.A. Hearing and Sound Communication under Water. In *Bioacoustics: A Comparative Approach*; Lewis, B., Ed.; Academic Press: New York, NY, USA, 1983; pp. 347–405.
39. Enger, P. Hearing in herring. *Comp. Biochem. Physiol.* **1967**, *22*, 527–538.
40. Fay, R.R. *Hearing in Vertebrates: A Psychophysics Databook*; Hill-Fay Associates: Winnetka, IL, USA, 1988.
41. Nachtigall, P.E.; Supin, A.Y.; Amundin, M.; Röken, B.; Møller, T.; Mooney, T.A.; Taylor, K.A.; Yuen, M. Polar bear *Ursus maritimus* hearing measured with auditory evoked potentials. *J. Exp. Biol.* **2007**, *210*, 1116–1122.
42. Wartzok, D.; Ketten, D.R. Marine Mammal Sensory Systems. In *Biology of Marine Mammals*; Reynolds, J., Rommel, S., Eds.; Smithsonian Institution Press: Washington, DC, USA, 1999; pp. 117–175.
43. Webster, D.R.; Popper, A.N. *The Biology of Hearing*; Springer-Verlag: New York, NY, USA, 1992.
44. Brill, R.L.; Sevenish, M.L.; Sullivan, T.J.; Sustman, J.D.; Witt, R.E. Behavioral evidence for hearing through the lower jaw by an echolocating dolphin (*Tursiops truncatus*). *Mar. Mamm. Sci.* **1988**, *4*, 223–230.
45. Mooney, T.A.; Nachtigall, P.E.; Castellote, M.; Taylor, K.A.; Pacini, A.F.; Esteban, J.A. Hearing pathways and directional sensitivity of the beluga whale, *Delpinapterus leucas*. *J. Exp. Mar. Biol. Ecol.* **2008**, *362*, 108–116.
46. Møhl, B. Hearing in Seals. In *The Behavior and Physiology of Pinnipeds*; Harrision, R., Hubbard, R., Peterson, C., Rice, C., Schusterman, R., Eds.; Appleton-Century: New York, NY, USA, 1968.
47. Keyon, K.W. Sea Otter *Enhydra lutris*. In *The Walrus, Sea Lion, Fur Seals and Sea Otter*; Handbook of Marine Mammals; Ridgway, S.H., Harrison, R.J., Eds.; Academic Press: London, UK, 1981; Volume 1, pp. 209–223.
48. Fleischer, G. Evolutionary principles of the mammalian middle ear. *Adv. Anat. Embryol. Cell Biol.* **1978**, *55*, 1–70.
49. Dallos, P.; Popper, A.N.; Fay, R.R. *The Cochlea*; Springer: New York, NY, USA, 1996.
50. Lim, D.J. Functional structure of the organ of Corti: A review. *Hear. Res.* **1986**, *22*, 117–146.
51. Pickles, J.O. *An Introduction to the Physiology of Hearing*; Academic Press: London, UK, 2003.
52. Ketten, D.R. Correlations of Morphology with Frequency for *Odontocetes cochlea*: Systematics and Topology. Ph.D. Thesis, The John Hopkins University, Baltimore, MD, USA, 1984.
53. Klischin, V.O.; Diaz, R.P.; Popov, V.V.; Supin, A.Y. Some characteristics of the hearing of the Brazilian Manatee, *Trichechus inunguis*. *Acoust. Mamm.* **1990**, *16*, 140–1440.
54. Szymanski, M.D.; Bain, D.E.; Kiehl, K.; Pennington, S.; Wong, S.; Henry, K.R. Killer whale (*Orcinus orca*) hearing: Auditory brainstorm response and behavioural audiograms. *J. Acoust. Soc. Am.* **1999**, *106*, 1134–1141.
55. Kastak, D.; Schusterman, R.J. Low-frequency amphibious hearing in Pinnipeds: Methods measurements, noise and ecology. *J. Acoust. Soc. Am.* **1998**, *103*, 2216–2228.
56. Møhl, B. Auditory sensitivity of the Common seal in air and water. *J. Audit. Res.* **1968**, *8*, 27–38.

57. Kastelein, R.A.; Bunskoek, P.; Hagedoorn, M.; Au, W.L.W.; de Haan, D. Audiogram of harbor porpoise (*Phocoena phocoena*) measured with narrow-band frequency modulated signals. *J. Acoust. Soc. Am.* **2002**, *112*, 334–344.
58. Johnson, C.S. Sound Detection Thresholds in Marine Mammals. In *Marine Bio-Acoustics*; Tavolga, W.N., Ed.; Pergamon: Oxford, UK, 1967; Volume 2.
59. Lurton, X. *An Introduction to Underwater Acoustics—Principles and Applications*, 2nd ed.; Springer-Verlag: Heidelberg, Germany, 2010.
60. Anderson, P.K.; Barclay, R.M.K. Acoustic signals of solitary dugongs: Physical characteristics and behavioral correlates. *J. Mamm.* **1995**, *76*, 1226–1237.
61. Demski, L.S.; Gerald, J.W.; Popper, A.N. Central and peripheral mechanisms of teleost sound production. *Am. Zool.* **1973**, *13*, 1141–1167.
62. Vester, H.I.; Folkow, L.P.; Blix, A.S. Click sounds produced by cod (*Gadus Morhua*). *J. Acoust. Soc. Am.* **2004**, *115*, 914–919.
63. Finstad, J.L.; Nordeide, J.T. Acoustic repertoire of spawning cod, *Gadus morhua*. *Environ. Biol. Fish.* **2004**, *70*, 427–433.
64. Wahlberg, M.; Westerberg, H. Sounds produced by herring (*Clupea harengus*) bubble release. *Aquat. Liv. Resour.* **2003**, *16*, 271–275.
65. Wilson, B.; Batty, R.S.; Dill, L.M. Pacific and Atlantic herring produce burst pulse sounds. *Proc. R. Soc. B* **2004**, *271*, 95–97.
66. Waters, R.; Engström, J.; Isberg, J.; Leijon, M. Wave climate off the Swedish west coast. *Renew. Energy* **2009**, *34*, 1600–1606.
67. Cato, I.; Kjellin, B. *Marine Geological Studies at the Wave Power Park Outside Islandberg, Bohuslän*; SGU Rapport 2008:10; Sveriges Geologiska Undersökning: Uppsala, Sweden, 2008.
68. Rossing, T.D. *Springer Handbook of Acoustics*; Springer: Berlin, Germany, 2007.
69. Nedwell, J.R.; Turnpenny, A.W.H.; Langworthy, J.; Edwards, B. Measurements of underwater noise during piling at the Red Funnel Terminal, Southampton, and observations of its effect on caged fish. Available online: http://www.subacoustech.com/wp-content/uploads/558R0207.pdf (accessed on 16 May 2013).
70. Madsen, P.T.; Wahlberg, M.; Tougaard, J.; Lucke, K.; Tyack, P.L. Wind turbine underwater noise and marine mammals: Implications of current knowledge and data needs. *Mar. Ecol. Progr. Ser.* **2006**, *309*, 279–295.
71. Bailey, H.; Senior, B.; Simmons, D.; Rusin, J.; Pickens, G.; Thompson, P.M. Assessing underwater noise levels during pile-driving at an offshore windfarm and its potential effects on marine mammals. *Mar. Pollut. Bull.* **2010**, *60*, 888–897.