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ACOUSTIC HARASSMENT DEVICE (AHD) USE IN THE AQUACULTURE INDUSTRY AND IMPLICATIONS FOR MARINE MAMMALS

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1. INTRODUCTION

In recent years, the number of aquaculture facilities using acoustic harassment devices (AHDs) in attempts to deter seals from approaching fish pens has increased, yet our understanding of the effects of these devices on both target and non-target species, in the short and long term, is still largely incomplete. This paper presents estimates of areas in which harbour porpoises (*Phocoena phocoena*) are likely to perceive and be affected by AHD sounds based on calculations using the source levels and attenuation characteristics of three different models of acoustic alarms used in marine mammal/fishery conflicts.

2. METHODS

Three device source levels with a low, medium and a high source level (SL) and two ambient noise limits (a very low and a high noise level) were used as input data for the calculations. For comparison, the low sound source used for this study was a commercial acoustic deterrent device (ADD) used in gillnet fisheries in attempts to reduce marine mammal bycatch and the medium and high sound sources were two models of commercial AHDs used on salmon farms in both North America and Europe. An estimate of the properties of the harbour porpoise hearing system was made (see below). The calculation results are the limits of the ADD and AHD audibility ranges under these conditions.

2.1 Source Level

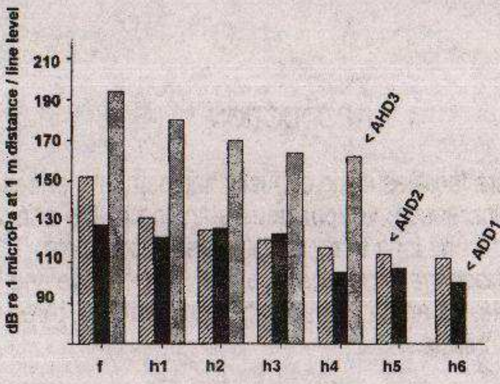
Very limited detailed acoustic data of ADDs and AHDs are available. We used 3 source level ranges:

ADD1, low-power:
: data derived from a *Netmark 1000 (2nd generation)* acoustic pinger of the *Dukane Company, St. Charles, ILL, USA*; detailed acoustic data in the frequency range of 0 - 100 kHz were measured by TNO-TPD; the pinger produced every 4.3 s an 11.3 kHz pulse with a duration of 300 ms; broadband SL was 130 dB re μPa at 1 m distance; levels of the fundamental frequency and harmonics are shown in Figure 1; the pinger produced frequency components (harmonics) higher than 100 kHz (levels above 100 kHz were not measured)

AHD2, medium-power:
: from Haller and Lemon [1] some data of an *'Acoustic Deterrent System'* manufactured by *Airmar Technology, Milford, NH, USA* can be derived; the device produced a complicated pattern of 10 kHz pulses (duration 1.8 ms, interval 40 ms); only the level of the fundamental (152 dB re 1 μPa) and the first harmonic was measured; Figure 1 gives these levels, as well as estimated levels of the other harmonics up to 100 kHz

AHD3, high-power:
: high-power AHDs can reach SL's of 200 dB re 1 μPa at 1 m distance, for instance the *Mk3 Seal Scrammer (Ferranti-Thomson, UK)*, produces a SL of 194 dB at 25 kHz, pulse duration 20 s; for the calculation, we took a signal consisting of 25 kHz pulses with assumed levels of the harmonics - see Figure 1.

Figure 1. Source levels of the 3 devices used in the calculations. Levels of the fundamental frequency component (f), as well as harmonics (h) up to roughly 100 kHz are shown. Fundamental frequencies are: ADD1 11.3 kHz, AHD2 10 kHz and AHD3 25 kHz. The levels are given in dB re 1 μPa at 1 m distance and refer to the RMS sound pressure level of the pulse. Only the levels of ADD1 were actually measured, the other levels were partly estimated.



2.2 Propagation

Sound propagation loss was calculated using a TNO-TPD computer model based on ray-tracing calculations. For comparison the input parameters were the same as in Haller and Lemon [1] which refer to a fishfarm located near Midsummer Island, BC, Canada: waterdepth 70 m; sound source depth 9 m; receiver depth 25 m; bottom 2 m thick sand/mud on a rock bottom; sound velocity 1482 m/s; wave height 0.3 m and signal frequency and distance variable. As a guideline, propagation loss for this particular situation, for frequencies above 10 kHz and for distances of 200 metres and more, can be characterised as [20 log (distance) - 3 dB]. This is in good accordance with the results of Haller and Lemon's study [1, Figure 14].

2.3 Ambient Noise and Audiogram

Figure 2 shows both ambient noise limits used in the calculations, given as *'isotrope, omni-directional spectrum level in dB re 1 μPa'*: a very low level based on sea state 1 [2] [3] and a high ambient noise level, measured by TNO-TPD in the Dutch coastal waters, with a large influence of wind, waves and the distant noise of sluices.

Figure 2. Ambient noise limits, used in the calculations: a high noise level (—) measured in the Dutch coastal waters and a very low level (------), based on the theoretical sea state 1 curves of Wenz [2] and Urick [3].

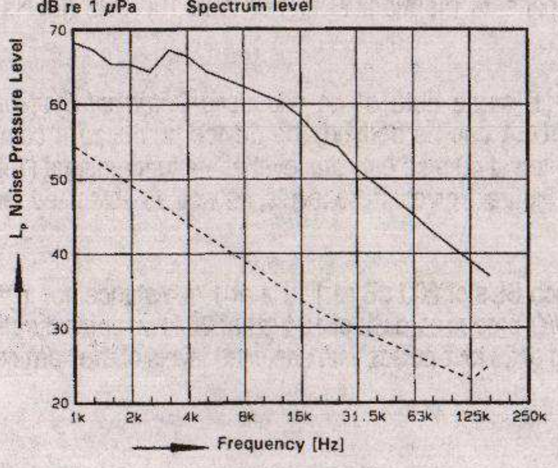
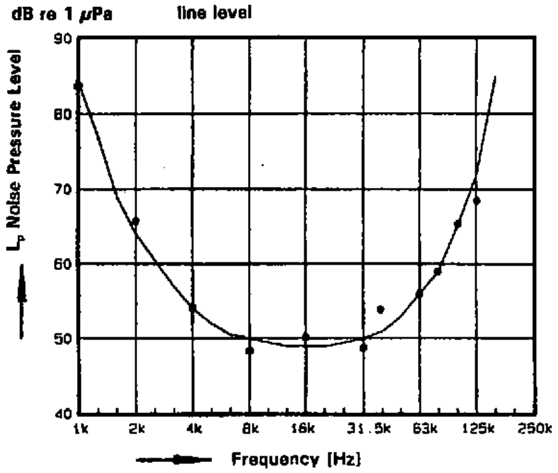


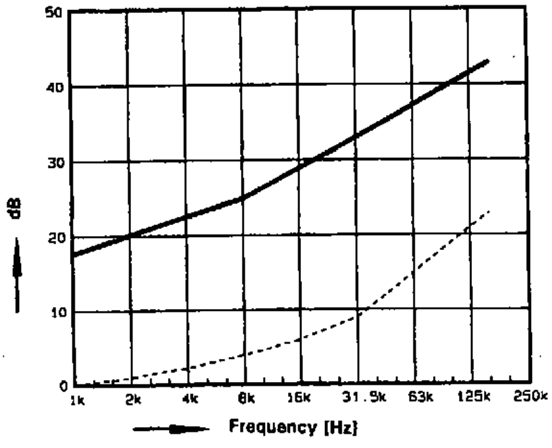
Figure 3. Audiogram of harbour porpoise (*Phocoena phocoena*): smoothed curve (—) and observations (•) of Andersen [4].



2.4 Critical Bandwidth
Data on the critical bandwidth or the critical ratio of the harbour porpoise hearing system and for other cetaceans are scarce. An estimation of the harbour porpoise critical bandwidth was made (see Figure 4) based on available data [5] [6] [7]; for pinnipeds: [8] [9] [10], as well as from relevant human data.

2.5 Directivity Index
The directivity index of the harbour porpoise receiving beam pattern is unknown. The pattern is estimated and the DI calculated using a formula in Urick [3, p42]. The beam pattern data of harbour porpoise receiving patterns at very low frequencies is probably roughly omni-directional, which means a DI of 0, confirmed by Andersen [4]. At the upper frequency limit of the porpoise's hearing system (160 kHz) it is probable that a rather narrow beam is formed. For bottlenose dolphins receiving beam patterns have been measured by Au and Moore [6] at frequencies of 30, 60 and 120 kHz. DI at these frequencies, calculated with a TNO-TPD computer model, were 8.9, 14.2 and 19.3 dB. Here, it is assumed that harbour porpoises have roughly the same receiving beam patterns as bottlenose dolphins. Figure 4 shows the estimated frequency dependent harbour porpoise DI's.

Figure 4. Hearing system of harbour porpoise (*Phocoena phocoena*): estimated values for the critical bandwidth (—) and for the directivity index of the receiving beam (------).



2.6 Zone of Audibility

The zone of audibility (ZA) is a spherical area around a sound source in which the sound can be detected by the animal, ranging from very weak to very loud. The radius of this area depends on:

- the sound pressure level of the source (source level, SL) in dB re 1 μPa at 1 m distance for a certain (analysis) bandwidth; for pulsed signals the level is the RMS value of the pulse sound pressure level ('line level'),
- the sound propagation loss between source and animal (transmission loss, TL); this loss is frequency dependent and (here) includes the effects of sound absorption; expressed in dB/km,
- the detection threshold (DT) of the animal's hearing system, in dB re 1 μPa 'spectrum level'; the DT depends on the properties of the animal's hearing system and is a combination of its:
  i. absolute audiogram (AA) in dB re 1 μPa 'line level'
  ii. critical bandwidth (CB) in dB
  iii. directivity index (DI) of the receiving beam pattern in dB
  iv. the isotrope, omni-directional ambient noise (AN) level at the animal's location, in dB re 1 μPa 'spectrum level'

  DT for *single-tone signals* is the highest level of AA and (AN+CB-DI), which means that at low and high frequencies AA determines DT and at mid-frequencies (AN+CB-DI).

The radius of the ZA can be found by combining (SL-DT) and TL and is frequency dependent. This calculation method is valid for (pulsed) tone signals and supposes that the animal's receiving beam is in the direction of the sound source. If the receiving beam is not in the direction of the sound source, ZA decreases (or even becomes 0).

3. RESULTS

The ranges of audibility for both ambient noise conditions were calculated and the results are summarised in Table 1. For these 3 devices, in principle, the fundamental frequency determines the radius of the zone of audibility. AHD3 has a smaller range than AHD2 (with lower SL) because of the higher fundamental frequency of AHD3 (more absorption). The ranges do not take into account pulse duration and pulse repetition rate: when pulses become short and/or rate becomes low, detection capabilities for single pulses are decreased, resulting in a decreased zone of audibility radius. However, harbour porpoise hearing system properties are unknown in this respect; for other marine mammals see: [7] [10] [11]. The range of AHD3 would be unaffected as its pulse duration is 20 seconds.

Table 1. Zones of audibility for both ambient noise conditions

ADD/AHD	zone of audibility high ambient noise levels	zone of audibility low ambient noise levels
ADD1	0 - 380 m	0 - 2790 m
AHD2	0 - 2770 m	0 - 12 190 m
AHD3	0 - 6880 m	0 - 10 140 m

3.1 Zone of Severe Disturbance and Discomfort

The zone of severe disturbance and discomfort is an area within which the sound level is very likely to be high enough to cause severe disturbance in terms of habitat exclusion or discomfort to the animal. For humans the corresponding sound level is 80 dB(A), which means that, when the sound source spectrum is corrected for the shape of the human audiogram, the total (broadband) level of the sound is 80 dB re 20 μPa (in air).

3.2 Zone of Hearing Damage and Injury

The zone of hearing damage and injury is an area within which the sound level is very likely to be high enough to cause hearing loss or tissue damage to auditory or other systems. For humans this occurs at approximately 130 dB(A).

The corresponding levels (in water) for harbour porpoises are unknown but an estimate was made, in favour of the animal, based on the following:

- the structure and dimensions of the hearing system of odontocetes and pinnipeds have a strong resemblance to those of humans; the shape of the audiograms are roughly the same, but frequency range differs strongly (as well as outer ear structure)
- the dynamic range of the human hearing system is approximately 140 dB; for odontocetes this range may be larger (because they produce loud signals); for pinnipeds this range may be equal to the human range or possibly somewhat smaller
- for humans the effects of high noise levels are known, for instance: discomfort and hearing loss after long-term exposure > 80 dB(A) and hearing damage and injury > 130 dB(A).

It is emphasised that although these criteria are based on extrapolating the properties and effects of the human hearing system to that of odontocetes and need to be verified by future studies, the effects of AHDs on harbour porpoises can at least be estimated. This was done by applying a similar 'weighting methodology' as the human dB(A) methodology.

3.3 Calculation of Weighting

The weighting method implies that the sound spectrum of the source is corrected for the shape of the (porpoise) audiogram (Figure 3), after which the total (broadband) sound pressure level (SPL) is calculated (= L_t). Table 2 gives the weighted levels of the 3 devices and the total level. See Taylor *et al.* [19] for methods.

Table 2. Weighted SPL's of the 3 devices in dB re 1 μPa

component	ADD1	AHD2	AHD3
f	127.5	151.5	193.5
h1	122	132	176
h2	126	125	160
h3	122	119	148
h4	101	113	139
h5	100	107	
h6	82	101	
L_t	**131**	**152**	**194**

Because the lowest (= most sensitive) hearing threshold of harbour porpoises in water is 50 dB re 1 μPa, the criteria levels for the various zones are:

Zone of severe disturbance and discomfort: $L_{t2} = 50 + 80 = 130$ dB re 1 μPa

Zone of hearing damage and injury: $L_{t3} = 50 + 130 = 180$ dB re 1 μPa

The level at which a sound source will be audible for harbour porpoises, but will probably not cause discomfort will be at 30 - 40 dB above hearing threshold (provided masking by background noise does not occur):

$L_{t1} = 80 - 90$ dB re 1 μPa.

Although these levels are assumptions based on the extrapolation of human criteria, a validation of these values can be found in Kastelein *et al.* [12] where the effects of pulsed sounds, with various frequencies and SL's, on a female harbour porpoise were determined. The observations were carried out in a shallow water pen, where local propagation losses, according to TNO-TPD measurements, fluctuated between [10 log (distance)] and [30 log (distance)]. When a sound source was switched on, the animal swam to a certain area in the pen of which the average distance to the sound source was determined. For the validation an average propagation loss in the pen of [20 log (distance)] was assumed, resulting in the observations summarised in Table 3.

Table 3. Observations of Kastelein *et al.* [12]

source	1 LU click	2 LU click	3 LU click	4 Scanmar	5 MUN1	6 MUN2	
frequency	140	70	35	110	2.5	2.5	kHz
average distance to source	20	22	17	30	10	10	m
SL	109	117	103	158	119	131	dB
SPL at average distance	83	90	78	128	99	111	dB re 1 μPa

These results, in general, confirm the criteria stated above:

- during activated sources 1 - 3 the animal swam to a location where the sound pressure level (SPL) was between 78 and 90 dB re 1 μPa; this is the criterion unlikely to influence the animal's comfort,
- source 4 caused the animal to swim to the pen corners, as far as possible away from the sound source; SPL in those corners was 128 dB re 1 μPa, a level which would cause severe disturbance; if the pen had been larger, the animal would probably have swum to a location with a lower SPL,
- during activated sources 5 and 6 the animal swam to an area where the SPL was somewhat higher than might be expected, namely 99 - 111 dB re 1 μPa; the reason the animal did not swim to a lower (for instance 80 dB) SPL location is not clear, but may be because the 2.5 kHz clicks were very familiar as harbour porpoises produce low-frequency echolocation clicks around 2 kHz [13] [14] [15].

Using the differences between the total weighted levels (L_t) of the devices in Table 2 and L_{t2} and L_{t3}, the radius of each zone of influence was calculated (Tables 4 and 5). Propagation conditions as mentioned earlier were applied.

Table 4. Zone of severe disturbance and discomfort; criterion is 130 dB re 1 μPa

	L_t (dB re 1 μPa)	difference (dB)	radius zone (metres)
ADD1	131	1	-
AHD2	152	22	17
AHD3	194	64	1030

Table 5. Zone of hearing damage and injury; criterion is 180 dB re 1 μPa

	L_t (dB re 1 μPa)	difference (dB)	radius zone (metres)
ADD1	131	-	-
AHD2	152	-	-
AHD3	194	14	7

4. DISCUSSION AND CONCLUSIONS

Based on the above calculations, we suggest that several commercial AHDs produce sounds loud enough to adversely affect harbour porpoises, and potentially other species of coastal marine mammals. Harbour porpoise populations around the world have been depleted through bycatch in a number of fisheries [16] and they are currently listed as 'threatened' by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC). A similar listing is still under review in the United States. There are growing concerns about the behavioural and physical impacts of such AHDs on both target species (generally pinnipeds) and on non-target species (odontocete cetaceans, some fish and potentially invertebrates as well) in the vicinity of operating devices. Marine mammals may be affected in many different ways by AHD sounds, ranging from physical and auditory damage, physiological and behavioural changes, to disruption of activities and displacement from important areas [17] [18] [19]. The extent to which a marine mammal may be affected by AHD sounds will depend on how close to the source they are and the type of device in use. Many assumptions are made when calculating ranges of acoustic influence and they are likely to vary with time, location, individual marine mammal and their motivation, and other factors. Despite these limitations, such estimates are useful in defining areas where marine mammals need protecting from some noisy human activities.

For the models of AHD used as deterrents on fishpens in this study, the zone of audibility for porpoises was calculated to range from a minimum radius of 2.8 km to a maximum radius of 12.2 km, with low ambient noise conditions in the local marine environment. These zones of audibility may represent a significant proportion of coastal habitat, especially where there are large congregations of fishfarms e.g. Quoddy Region, Bay of Fundy, Canada [20]. In these areas, porpoises may perceive AHD noises as a threat and avoid them. In such instances their habitat would be effectively reduced and movements between important areas potentially limited [20] [21] [22]. There is some evidence to support this hypothesis as significant reductions in porpoise abundance within 3.5 km of an active AHD have been documented previously [21]. The same study reported that porpoises were totally excluded from within 400 m of the sound source. Our calculations suggest that severe disturbance (and potentially temporary loss of hearing) of porpoises will occur at distances between 17m and approximately 1 km (depending on the model of AHD and ambient noise) from the sound source, corresponding well with the data of Olesiuk *et al.* [21]. There are also other anecdotal data supporting this hypothesis. Morton [23] documents a reduction of sightings of killer, gray, minke and humpback whales in the Broughton archipelago after the introduction of AHDs on salmon farms and Strudwick [24] also documents reductions in both common (harbour) seals and harbour porpoises around salmon farms using AHDs in Scotland. The distance to which animals were excluded in both study areas is currently unknown. There are also a few documented cases where sounds have been shown to alter the distribution and behaviour of some fish [25] [26] [27] and, in theory, could also affect the foraging behaviour of odontocetes and pinnipeds.

Along with displacement and disturbance effects caused by AHDs, actual physical damage may occur to animals that are very close to the source. Theoretically, within 7 metres of source AHD3 immediate hearing damage and injury could occur to a harbour porpoise. Hearing impairment caused by AHD noise could seriously compromise the ability of an exposed marine mammal to navigate, detect prey and, in the case of odontocete cetaceans such as the harbour porpoise, the ability to echolocate. Some models of AHDs can be triggered manually, or by net sensor, at full power. Exposing animals to such high levels of noise clearly affects their welfare and may, in the long term, be counterproductive; individual seals that are deaf will not notice AHDs and deafened porpoises may not detect ADDs deployed on gillnets in attempts to reduce bycatch.

As in most human-animal conflicts, single solutions are unlikely to be universally applicable. Acoustic harassment devices should only be used in conjunction with, and after, other non-acoustic, non-lethal, anti-predator methods [28]. Acoustic harassment devices that are triggered manually or by net sensors should be modified to ramp up slowly, and tested to determine their effectiveness in allowing animals the time to move away from the source. For conservation and animal welfare reasons, source levels of AHDs in use on fish pens should be limited to below the zone of severe disturbance and discomfort of odontocete cetaceans resident in the particular locality. There is still a need for experimental evidence that AHDs significantly reduce predation on penned or caught fish [28]. Studies on the effects of high-energy sounds produced by AHDs on marine mammals (target and non-target) and other organisms are also needed, particularly as the re is growing evidence that noise can have significant detrimental effects on non-target species.

Our results indicate that some AHDs may pose a threat to marine mammals, particularly in the form of habitat exclusion. Considering the extent of AHD use world wide [19] and our lack of understanding on their effects, some marine mammal populations may have already been adversely affected. Clearly, more research is required to better determine the ranges at which AHD noises become threatening or damaging for marine mammals and to resolve conservation issues related to AHD induced habitat exclusion.

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