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Hull-mounted hydrophones for passive acoustic detection and tracking of sperm whales (*Physeter macrocephalus*)

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Abstract

Acoustic monitoring has proven increasingly important for detection and tracking of marine mammals. Most systems rely on towed hydrophones that can be cumbersome to deploy and pose a risk in terms of fouling propellers and failing in rough seas. To alleviate these problems, an acoustic detection system designed for monitoring and tracking vocally active marine mammals, sperm whales in particular, has been developed. The system uses two hydrophones, designed for hull-mounting on each side of the keel of small as well as larger vessels. The system is relatively simple to use and does not require deployment of any equipment.

Hydrophone outputs are amplified and filtered by a custom built conditioning circuitry. Bearing is estimated by manoeuvring the vessel to minimize the difference in level between the two hydrophones. Forward-aft ambiguity is resolved by turning the vessel. The system permits acoustic bearing estimations to be carried out while cruising at speeds of 5 knots. The theoretical maximum detection distances of sperm whales are several kilometres, depending on the relative orientation of the animal.

Keywords: Hull-mounted hydrophone; Sperm whale; Tracking; Acoustic detection; Bearing estimation

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1. Introduction

During the last decades conservation and management of marine mammals have become increasingly hot topics. Human activities have affected marine mammals in all oceans by whaling, fishing, pollution, oil exploitation and increased shipping with noise pollution as a consequence. Accordingly, monitoring the population sizes of marine mammal species is now more important than ever.

Using conventional visual observation techniques, the sperm whale (*Physeter macrocephalus*) is one of the challenging species of the great whales to survey. They live off the continental shelves worldwide. Feeding mainly on meso- and bathypelagic squid and fish [1] they perform dives, which may last for an hour, resting only about 10 min at the surface between dives [2]. This makes them difficult subjects for visual observations, both because of the relatively short time spent at the surface as well as the logistical problems investigators encounter when monitoring whales in off shore waters. Detecting sperm whales by means of vision requires good conditions regarding wind, sea state, light, and visibility. Furthermore, keeping watch for several hours is a demanding task, and requires the participation of several trained people if the entire horizon is to be watched simultaneously.

However, the fact that sperm whales generate very powerful, distinctive clicks [3], with regular intervals within the human audible frequency range makes them suitable for acoustic observations. The clicks from sperm whales may be detected at distances of several miles. Combining an acoustic detection system with a tape recorder or a standard PC with a sufficiently large memory offers the possibility of automatically logging information for subsequent analysis. If required, the detection system can be made automatic, eliminating errors due to inter-observer variability.

In the light of the above, many researchers have applied acoustic techniques when working with sperm whales as well as other marine mammals. Some techniques have involved floating arrays of hydrophones with the purpose of localising the whales [4]. This has proven useful when studying sperm whale social behaviour, diving patterns, etc. and has been essential when estimating the source levels and directionality of the emitted sounds from the sperm whale [5]. Likewise bottom-mounted arrays have been used for acoustic monitoring of large baleen whales [6,7], as well as for sperm whales in the Gulf of Alaska [8].

In other contexts, the ability to determine bearings to the whales by means of their emitted sounds has been useful, often as a supplement to visual observations. The simplest method used is the directional hydrophone. Because of the inherent directional properties of the hydrophone, an estimated bearing to the vocalizing animal can be obtained simply by turning the hydrophone until the most powerful signal is received (see e.g. [9]).

Another approach is the use of towed arrays. With two or multiple hydrophones it is possible to obtain bearings to vocalizing whales from time of arrival differences, while cruising at speeds of more than 4 knots [10]. Such systems consist of two or more hydrophones towed after the research vessel at some distance, thereby reducing masking effects of propeller- and engine noise from the boat and assuring some depth of the hydrophones. Inherent problems of towed arrays are that they can be cumbersome to handle, and that they may limit manoeuvrability and speed.

In this paper an acoustic detection system based on two hull-mounted hydrophones is described. Calibration test results as well as field data are presented and we discuss the performance of the system.

2. Materials and methods

The sound receivers of the system consist of two custom-built hydrophones, each containing a piezoelectric element as a pressure-to-voltage transducer. When calibrated, it is possible, from the out-coming voltage, to calculate the sound pressure impinging on the hydrophone. Furthermore, every piezoelectric element has a resonance frequency. At this frequency, the element will have the highest sensitivity, thus effectively applying a band pass filter around the resonance frequency. In general, large piezoelectric elements have a high sensitivity and a low resonance frequency, whereas small elements have low sensitivity and high resonance frequency.

Usual clicks of male sperm whales have maximum intensity in the 5–20 kHz range [3]. Hence, the piezoelectric elements used were circular discs of Pz 21 (Ferroperm), chosen so as to ensure that the resonance frequency of the elements, when mounted on the back plate (see below), would be at about 10.5 kHz. This made the hydrophones very sensitive to sperm whale clicks, while passively filtering out low frequency noise from engine and propeller.

The piezoelectric element of each hydrophone was mounted on a lead back-plate and placed on top of 10 mm of closed cell foam to reduce vibrations originating from the hull. Piezoelectric element, lead back-plate, and closed cell foam were embedded in polyurethane, shaped so as to minimize water drag and flow noise when mounted on the ship hull (see Fig. 1). Hydrophones have been mounted on each side of the keels of r/v Narhvalen, a 45 ft steel ketch (Fig. 2), and m/s Reine, a 100 ft whale watching boat with a wooden hull.

Signals from the hydrophones mounted on r/v Narhvalen were amplified using Grass P15 amplifiers with a one pole high pass filter set at 300 Hz (−6 dB/octave). The hydrophones on m/s Reine were connected, via a preamplifier, to a conditioning box with adjustable gain- and filter settings as well as peak meters showing hydrophone output. An operator equipped with a pair of headphones would monitor incoming signals. The human auditory system serves as an excellent click detector when pertaining to sperm whale clicks, and due to stereo-effect between left and right channel, the operator

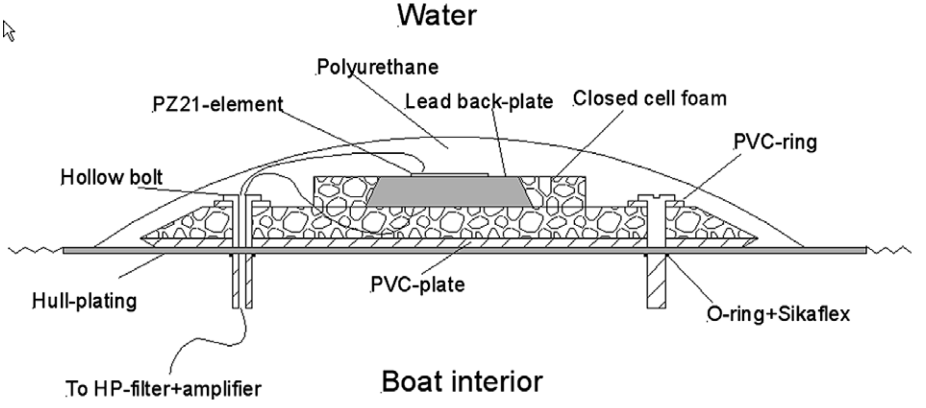

Fig. 1. Schematic drawing of hull-mounted hydrophone.

Fig. 2. Hydrophones mounted on r/v Narhvalen. Frontal and side view.

would be able to determine whether a given signal was on the portside or the starboard side of the boat. Signals were recorded on a Sony DAT-recorder TCD-D7.

In practice, the procedure used for finding a bearing to a whale was as follows: when the hydrophone operator detected a whale clicking on the hydrophones, the boat would be turned slowly in the direction of the side where the signal would be of the highest amplitude. The boat would be turned until the signal was strongest on the opposite hydrophone. Then the boat would be turned slowly back again. This procedure would be repeated until the operator was confident that the signals on the two hydrophones were equally strong. At this time, the bearing to the whale would simply be the heading of the boat.

For subsequent analysis some sequences were high pass filtered at 6 kHz, using standard PC sound editing software (Cool Edit, Syntrillium).

Field data were collected during the summers of 1998, 2000 and 2001 at Andenes, northern Norway (N69°; E15°).

2.1. Calibration

Sensitivity calibrations of the hydrophones on r/v Narhvalen were carried out by emitting 1.3 ms pulses with frequencies from 2.5 to 19 kHz, using a custom-built piezoelectric ceramic pinger. A Brüel & Kjær 8101 hydrophone was used as reference. A frequency response curve was generated and the $Q_{-3\,\mathrm{dB}}$ value calculated. The frequency response curve was used for calculating the effective bandwidth.

The bearing resolution capabilities of the hydrophone system on r/v Narhvalen were determined by emitting pulses with a custom-built piezoelectric ceramic pinger (sweep 30–10 kHz, duration 2 ms) at different angles relative to the axis of the boat. The pinger source level was kept constant during this procedure. Voltage output of the two hydrophones was plotted as a function of angle. The resonant characteristics of the hydrophone and the steel hull of r/v Narhvalen resulted in a time resolution that made time of arrival differences unobtainable with the small spacing of the hydrophones in this setup.

3. Results

3.1. System calibration

Results of the pinger calibration are shown in Fig. 3. The output levels from the hydrophones decrease as the pinger is moved from ipsilateral to the contralateral side. Note that moving the pinger from 15° port to 15° starboard causes the output to change 14 and 12 dB on the starboard and port hydrophone, respectively. This is attributed to a shielding effect of the keel on which the hydrophones are mounted. Thus, the keel induces directionality to the system thereby enhancing derivation of bearing estimates. Sensitivity calibration of the system yielded a frequency response with a maximum sensitivity of −195 dB re 1 V/μPa at 10.5 kHz and a $Q_{-3\,\mathrm{dB}}$ value of 4 kHz. The relative noise spectrum level was calculated for the recording sequence shown in Fig. 4a, representing the noise when motor-cruising at a speed of approximately 5 knots. The flow-, engine- and system noise was found to set the noise floor and not the ambient noise.

3.2. Detection distance

The clicks from sperm whales are highly directional. Thus, when estimating the detection range a distinction was made between clicks recorded on the acoustic axis of the whale and clicks recorded off the acoustic axis of the whale. Source levels were presumed to be 236 dB re 1 μPa (rms) and 180 dB re 1 μPa (rms) on the acoustic axis and off the acoustic axis, respectively [3,5]. To simulate the response of the hull-mounted hydrophones, broad band recordings of both on-axis and off-axis sperm whale clicks were run through a Butterworth 1 pole band pass filter, resembling the inherent band pass filter of the hydrophones. The band pass filtering reduced the amplitude of the on-axis sperm whale signal by 5 dB and the off-axis signal by 8 dB. For the sake of comparison, the noise in Fig. 4a

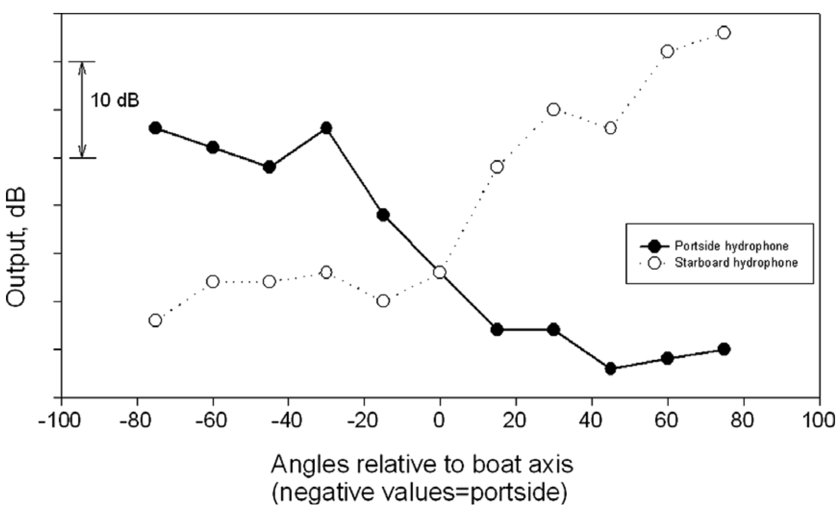

Fig. 3. Pinger calibration of hydrophones at fixed source levels. Negative numbers on the abscissa correspond to portside angles; positive numbers correspond to starboard side angles.

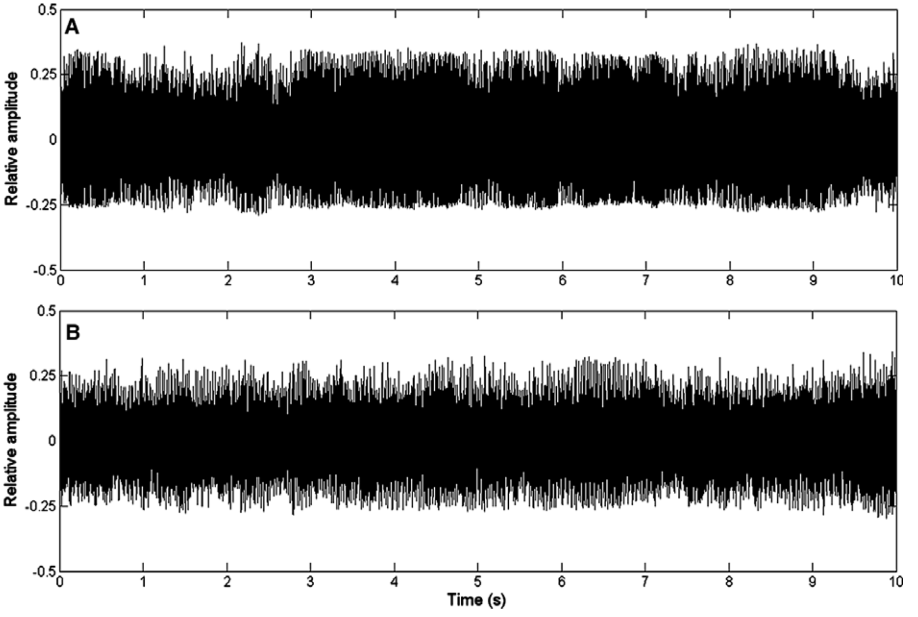

Fig. 4a. Recorded track showing clicks from a single sperm whale. Clicks are hidden in the noise. Recorded while cruising with ≈5 knots. No subsequent filtering.

was subjected to the same filtering as the sperm whale clicks mentioned above. Using a detection threshold of 3 dB above the combined system and recorded noise level of 96 dB re 1 μPa (rms) in the 4 kHz pass band around 10 kHz, the theoretical maximum distance of detection could be estimated, from source levels of 231 and 172 dB re 1 μPa (rms) using the noise limited passive sonar equation [11]. Spherical spreading was assumed, and loss due to absorption (1 dB/km at 10 kHz) was included in the calculations. The estimated detection ranges were some 3 km and 40 km for off- and on-axis clicks, respectively.

3.3. Andenes field data

Fig. 4a shows a recording of clicks from a single sperm whale. The recording was made on r/v Narhvalen while motor-cruising at a speed of approximately 5 knots (9 km/h). Despite a poor SNR (signal to noise ratio), the recorded clicks can be easily heard. However, for subsequent analysis this does not suffice. Fig. 4b shows the same sequence after high pass filtering at 6 kHz. Although some low frequency noise still remains, clicks on the upper channel are now easily identifiable. The whale detected on the portside hydrophone (upper trace) is not visible on the lower trace.

Fig. 4c demonstrates an example of a recording where r/v Narhvalen is drifting with the engine off. Clicks from two whales are visible, one on the upper channel and one on the lower channel.

Power spectra of the noise in Figs. 4a and 4c are presented in Fig. 5. The upper curve corresponds to the noise from the track in Fig. 4a, i.e. when cruising with a speed of approximately 5 knots. The lower curve is the spectrum obtained from the noise in Fig. 4c, representing a situation where the boat is drifting with the engine turned off.

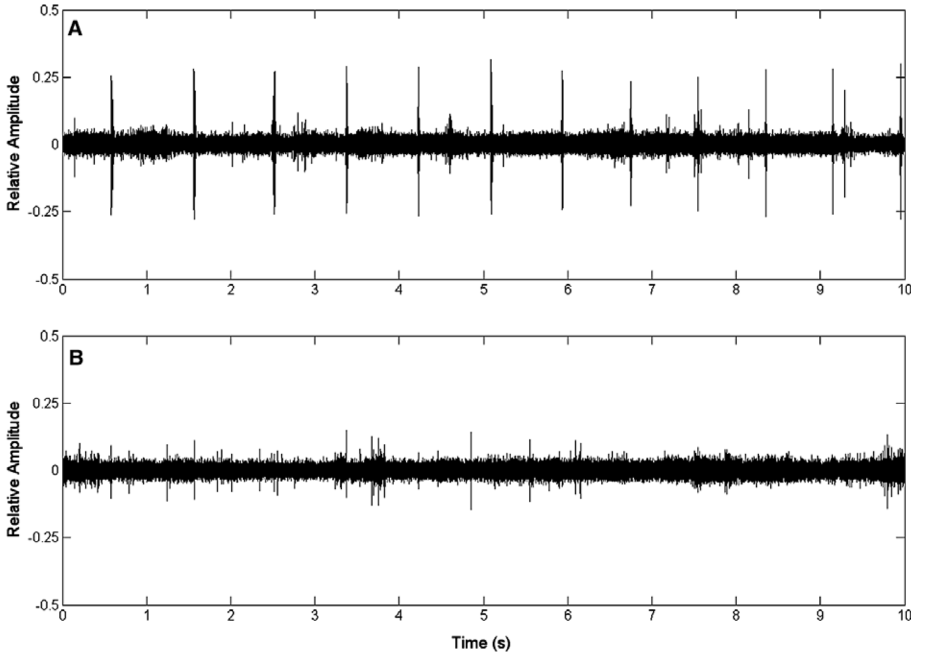

Fig. 4b. Same track as in Fig. 4a, but high pass filtered at 6 kHz.

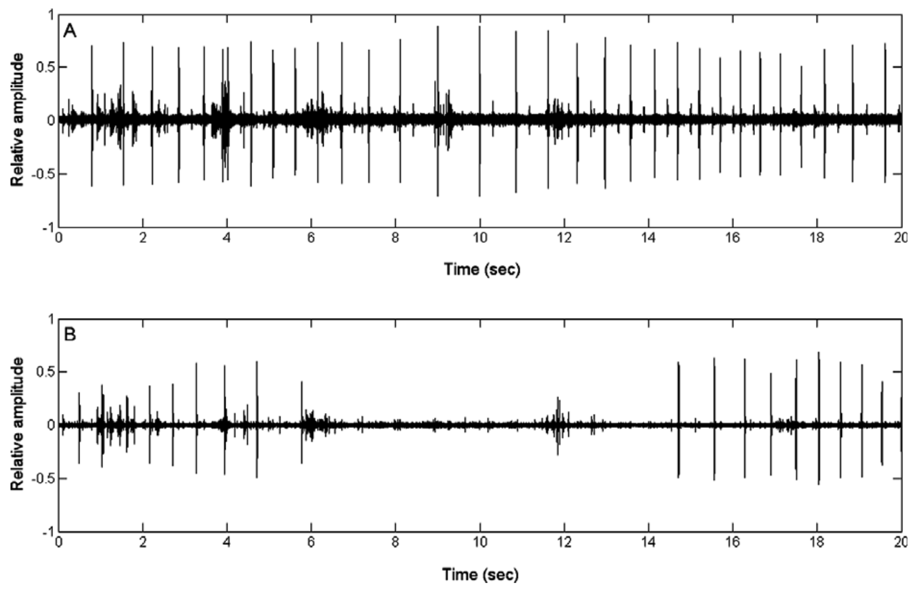

Fig. 4c. Track showing clicks from two whales, one on each channel. High pass filtered at 0.3 kHz. Recorded while drifting with the engine off.

A peak at 10.5 kHz, representing the resonance frequency of the hydrophones, can be identified on both traces. Note that there is essentially no difference in the noise level above 6 kHz, indicating that engine- and flow noise as well as noise from the propeller is mainly a

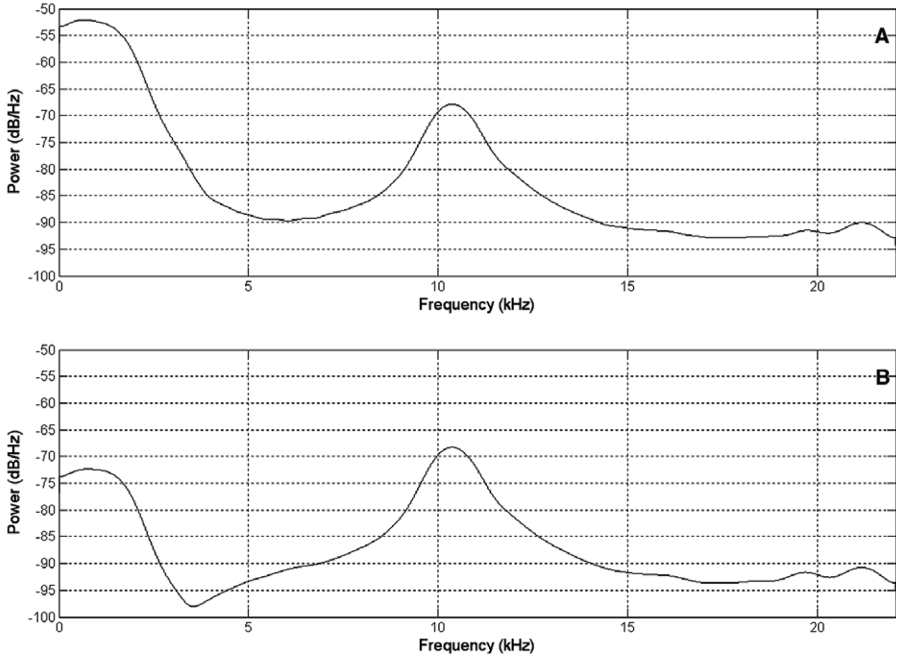

Fig. 5. Spectrum of noise measured in the track displayed in Figs. 4a and 4b. Arbitrary but identical reference. Upper trace corresponds to noise from Fig. 4a; lower trace corresponds to noise from Fig. 4c. Bin width 23 Hz.

low frequency phenomenon, and does not interfere markedly with the analysis band around 10 kHz, used for detecting sperm whale clicks, thus rendering estimated detection ranges the same, no matter if motor-cruising or not.

Fig. 6 shows a single sperm whale click recorded from the hull-mounted hydrophones on r/v Narhvalen. The signal is equally strong on both hydrophones, indicating a bearing to the whale aligned with the longitudinal axis of the ship. Three separate pulses, with a separation of about 6 ms, are visible within the click, thus demonstrating the multi-pulse structure found in some recording aspects of sperm whale clicks.

Because m/s Reine is a larger vessel than r/v Narhvalen, the hydrophones were mounted further apart, thus making time of arrival differences of clicks more obvious than was the case with clicks recorded on r/v Narhvalen. Fig. 7 demonstrates a click from a sperm whale located on the starboard (upper trace) side of m/s Reine. There is an amplitude difference of some 10 dB between the two channels and a time of arrival difference of 0.46 ms, corresponding to a difference in travel path of approximately 0.7 m.

4. Discussion

4.1. Alternative techniques

None of the present acoustic alternatives to traditional visual observation techniques are without problems. Floating arrays offer the opportunity of high precision positioning and bearing estimation to whales. However, deploying floating arrays is an onerous task and moving the array is not a simple job.

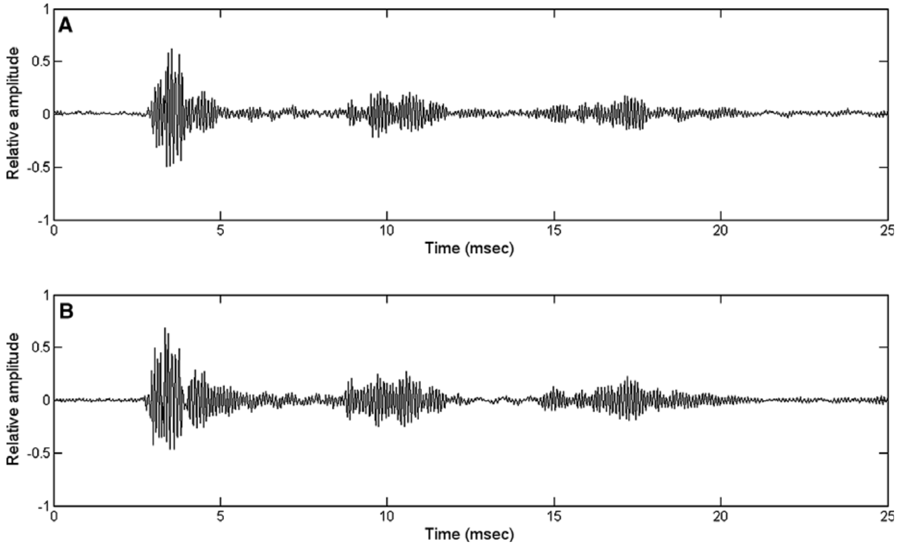

Fig. 6. Single sperm whale click recorded on r/v Narhvalen, showing multi-pulse structure. No subsequent filtering.

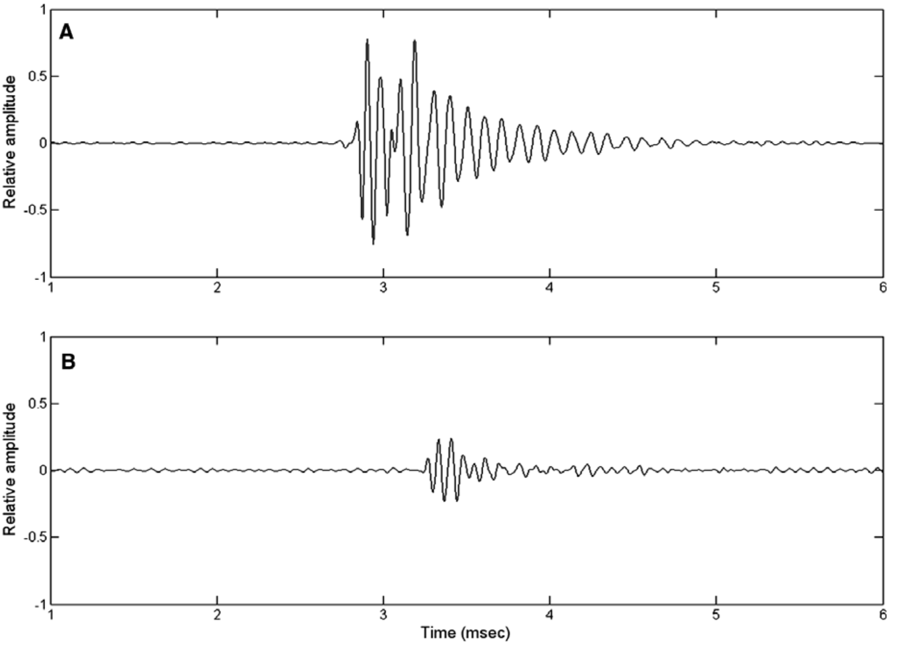

Fig. 7. Single sperm whale click recorded from hydrophones on m/s Reine. The animal was located on starboard side of the boat, corresponding to the upper trace. Note time- and amplitude differences.

As is the case with floating arrays, bottom-mounted hydrophone arrays also make it possible to determine the position of underwater sound sources with fairly high accuracy. Unfortunately this kind of acoustic monitoring is very expensive and can only be conducted in a predetermined area.

If determining bearings suffices, the directional hydrophone offers a low-cost alternative to the methods mentioned above. However, a shortcoming of this method is the necessity of stopping the research vessel every time the hydrophone is to be lowered into the water. Additionally, the directional hydrophone will typically be situated close to the surface, making it susceptible to ship- and wave noise. Stopping the boat every time the hydrophone is to be put into the water greatly affects the speed with which an acoustical survey can be carried out. In spite of the shortcomings of the directional hydrophone, a number of researchers have used it because of its simplicity and reliability (e.g. [10,12]).

The use of towed arrays overcomes some of the problems mentioned above. With this technique, the problems of masking effects of propeller- and engine noise from the boat as well as wave noise have been overcome to some extent. Also, the technique offers the possibility of covering large areas in short time. Nevertheless, the system has the disadvantage of requiring the deployment of the hydrophones plus cables at every recording session. Leaper et al. [10], in their surveys, used two hydrophones, towed behind a boat with 100 m of cable. Clearly, towing some 115 m of equipment behind a boat influences manoeuvrability, not to mention the risk of fouling up the propellers. Furthermore, the deployment of the hydrophones requires an experienced crew, and even then it is a time consuming process. Another disadvantage of the towed hydrophones is the necessity of doing relatively complex onboard calculations to obtain bearings, requiring computer hardware installed on board the research vessel.

4.2. Properties of the hull-mounted hydrophones

As appears from the system calibration (Fig. 3) the system does not rely on giving accurate bearings by calculating amplitude differences between the two hydrophones. Fig. 3 shows that such calculations would be confounded by considerable uncertainty at the small hydrophone spacing found on r/v Narhvalen. An exception from this is when a sound source is located right behind or in front of the vessel.

Nevertheless, due to the shielding effect of the keel the system becomes very sensitive to bearing differences of only a few degrees relative to the stem-stern axis and because of this, it is possible to home in on the direction to a sound source.

The calculating of bearings by time of arrival differences of clicks impinging on the two hydrophones was abandoned at a relatively early stage due to the resonant characteristics of the hydrophones and the steel hull on r/v Narhvalen which made the time resolution rather poor. However, the combination of larger distance between the hydrophones and a wooden hull seems to alleviate these problems to some extent, as demonstrated in Fig 7. Applying standard software (available as freeware on the Internet) to the system will probably be a future feature, hence automating the bearing estimation.

The ability to use the system while cruising was considered to be important when designing the system, since this greatly affects the speed by which acoustic tracking and counting can be conducted. Figs. 4a and 4b demonstrate the effect of subsequent high pass filtering of sperm whale signals recorded while cruising with a speed of approximately 5 knots. The clicks, which are hard to identify in Fig. 4a, appear clearly in Fig. 4b. Despite a poor SNR, the clicks in Fig. 4a can easily be distinguished by a trained operator equipped with a pair of headphones.

The reason why a simple high pass filter has such an effect as demonstrated in Figs. 4a and 4b appears from Fig. 5. The difference between the upper and lower trace (i.e. the cruising- and drifting situation, respectively) shows that the main part of the noise in the cruising situation appears below 3.5 kHz, thus making it relatively straightforward to remove by applying a high pass filter. The peak at 10.5 kHz in both traces indicates the resonant characteristics of the hydrophones.

Despite the resonant characteristics of the hydrophones, the time resolution capabilities proved to suffice for the purpose of finding characteristics of sperm whale clicks, such as the multi-pulse structure demonstrated in Fig. 6. Thus, in the case of the sperm whale, the system offers the possibility of species recognition and length estimation. Using the equation derived by Gordon [13], the click in Fig. 6 would be from a specimen with a length of approximately 12 m.

The system has a theoretical maximum detection range, regarding sperm whale clicks, of some 40 km or 3 km, depending on whether the whale is directing its sonar beam directly towards the hydrophones or the hydrophones are receiving off-axis clicks. The theoretical detection distance regarding off-axis clicks is supported by experiences during recordings in the field. The ability to detect a sperm whale at a distance of 40 km must, however, be regarded as a theoretical maximum. The highly directional character of sperm whale clicks [5] makes the probability of receiving a true on-axis click very small. Furthermore, the ability to detect whales at long range will be affected by the sound velocity profile of the water column. On the other hand, a detection threshold of 3 dB is probably a conservative estimate, which means that off-axis clicks may very well be detectable at distances greater than 3 km.

Calculating the maximum detection distance, we chose the noisiest situation (i.e. when r/v Narhvalen is motor-cruising) as the background noise reference. However, although there is a significant difference between the background noise when cruising and drifting, there is no reason to believe that this difference will have any dramatic effect in terms of changing the maximum detection distance. As appears from Fig. 5, the noise from propeller, engine and flow turbulence is mainly present at frequencies below 6 kHz, thus not masking the sperm whale signal, with its frequency emphasis at 8–12 kHz.

4.3. Conclusion and perspectives

The hull-mounted hydrophones presented in this paper constitute a reliable, handy, and relatively inexpensive alternative or supplement to existing acoustic monitoring techniques. They are suited for all kinds of vessels, regardless of size, and allow acoustical tracking to be carried out with a minimum of resources and training. The inherent characteristics of the hydrophones make it possible to use the system while cruising at relatively high speed, thus enabling surveys to be carried out in large areas efficiently.

The hydrophones were designed for obtaining bearing estimates to sperm whales, but the system offers the possibility of further development, since it is relatively straightforward to alter the frequency characteristics of the system to match the signals from other marine mammal species. However, one should be aware that using the system on very low frequency sounds (like the calls from large baleen whales) will reduce the accuracy, as the shielding effect of the keel will be small at long wavelengths.

Combining the hull-mounted hydrophones with existing technology from bat-detectors (divide by 10 or heterodyne analyser) would enable the system to detect high frequency sounds, thus making it applicable to a number of other odontocete species which emit sounds beyond the upper human hearing limit. Because of the ability to cover large areas within a relatively short time span, the system could prove to be a valuable tool in the future when estimating population sizes, possibly supplementing other existing monitoring methods.

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