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Estimation on Audibility of Large Cetaceans for Improvement of the Under Water Speaker

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ABSTRACT: In order to avoid collisions between the hydrofoil (HF) and cetaceans, the Under Water Speaker (UWS) has been installed on the HF. Because of its potential in utility, we tried to improve the UWS to minimize the risk of the collisions. Under our project, we examined three subprojects; 1) Analyzing the characteristics of the HF underwater noise; 2) Assessing audibility of major large cetaceans by measuring their vocalizations and 3) An anatomical prediction of the audible range by examining the cochlear basal membrane. Through the analyses, it was identified that the noise produced by the HF was a broad-band noise with approximately 150dB *re* 1µPa-m.That noise level was lower than those of larger boats suggesting difficulties for cetaceans in sensing approach of the vessels. In addition, analysis of their vocalizations and anatomical obervation indicated that dominant frequency of their audible range was lower than signals produced by the existing UWS.

1 INTRODUCTION

The Under Water Speaker (UWS) has been installed on the hydrofoils (HF) for avoiding the collisions with large cetaceans. However, its utility is still uncertain whether the sound produced by the UWS corresponds to the audible range of major large cetaceans. This is a major reason why we conduct the present study which explores the way to improve the UWS from biological aspects. Under the present research project, we examined three sub-projects:

1.1 *Characteristics of the HF underwater noise*

One of the reasons of the collision is considered that the HF underwater noise is possibly hard for cetaceans to recognize approaching vessel. It is probably because the noise level is too low and hardly transmits to a long distance. Therefore we analyze the characteristics of the HF underwater noise.

1.2 *Assessing audibility by measuring of vocalization*

The UWS should be improved to prevent the collision incorporating with the audible range of causal cetaceans. Currently, there are no direct measures of audible range for any large cetaceans because they cannot be investigated with conventional audiometric techniques of psychoacoustical or electrophysiological analysis. However, the audible range can be assessed by vocalization, as to correspond the dominant frequencies of the vocalization (e.g. calls) to the most sensitive region of receptor system in vertebrate taxa (Green and Marler 1979). Shakata *et al.* (2008) identified sperm whale (*Physeter macrocephalus*), Baird's beaked whale (*Berardius* *bairdii*), common minke whale (*Balaenoptera acutorostrata*), Bryde's whale (*Balaenoptera edeni*) as possible causal species of the collision on the sea route of the HF in Japanese water. Among these species, we chose to sample the vocalization of sperm whale and Bryde's whale since relatively easier to record their vocalizations in Japanese water. Based on the recorded vocalization, we assessed the audible range of these species.

1.3 *Anatomical Predictions of the Audible range*

Alternatively, a comparative anatomy approach is the useful way to estimate the audible range because anatomical structure of inner ear correlates to frequency range in multiple mammalian species (Echteler *et al.*, 1994). In particular, the cochlear configuration and thickness to width (T/W) ratios of the basilar membrane in inner ear are consistent with the maximal and minimum frequencies for each cetacean species (Ketten and Wartzok, 1990). This study estimates the audible range of common minke whales and Baird's beaked whale by describing the anatomy of their inner ears and applying the model described by Ketten (2000).

2 METHODS

2.1 *Characteristics of the HF underwater noise*

Underwater noise of the HF, SUISEI: 169gt. LOA31.2m (Owned by Sado Kisen Co.,Ltd.), was recorded during its cruise at service speed (38-39kn) from a small vessel at a distance of 100m. Recordings were made using a OKI SEATEC model OST2130 (frequency response 10Hz to 100kHz) omnidirectional hydrophone has sensitivity of approximately -174±3dB *re* 1V/μPa with 10m cable. It was connected via pre-amplifiers (frequency response from 20Hz to 20kHz), on a Sony PCM-D50 digital recorder (16bit 44.1 kHz) and OKI SEATEC OST4100 Hydroacoustic analyzer which was used to analyze the sound source level. This recording chain had a flat frequency response from 20Hz to 20 kHz. The HF underwater noise was assessed by 1/3-octave bands analysis using Avisoft SASLab Pro (Avisoft Bioacoustics, Germany.Ver.4.1.) because noise levels in 1/3-octave bands are useful in interpreting noise effects on animals. The estimated source levels of underwater noise (at 1m) of the HF were calibrated by Transmission Loss and Absorption Loss (Francois & Garrison1982).

2.2 *Assessing audibility by measuring of vocalization*

Bryde's whale sounds were recorded in the waters of Kochi on the south western coast of Japan (32º40' to 33º2'N, 133º00' to 133º13'E) for five days in mid-October, 2008. The study area ranged from the south coasts out to approximately 30km (16 nmi) of the shore. We chartered a fishing-boat for recording. When cetaceans were sighted, the boat approached to confirm species and school size and to collect other relevant information. When sighting Bryde's whale, the hydrophone was thrown in water and started recording. Signals were recorded with a OKI SEATEC model OST2130 omnidirectional hydrophone with 15m cable, connected via pre-amplifiers (frequency response 20Hz to 20kHz), on a Sony PCM-D50 digital recorder(16bit 44.1 kHz). This recording chain had a flat frequency response from 20Hz to 20 kHz. The acoustic characteristics of phrases were examined by using the analysis software Avisoft SASLab Pro, with spectrogram parameters of 512-point FFT size, 75.0% overlap, and Hamming window. The vocalization was analyzed based on the following parameters; duration, peak frequency, and fundamental frequency of element.

Sperm whale sounds were recorded off the southeastern coast of Chichijima, the Bonin (Ogasawara) Islands (26º55' to 27 º05 'N, 142º11' to 142º24'E) for eight days in September, 2009. We chartered a fishing-boat for recording. When sperm whales were sighted the boat approached to confirm school size and to collect other relevant information. When sighting sperm whale, the hydrophone was thrown in water and their vocalization was recorded. Signals were recorded with recording system described above in Bryde's whale sounds recording.

2.3 *Anatomical Predictions of the audible range*

Ear bones of 9 specimens of common minke whales (9 individuals) and 6 of Baird's beaked whales (3 individuals) were collected (under cooperation with The Institute of Cetacean Research, Tokyo Japan and National Research Institute of FarSeas Fisheries, Yokohama Japan) and analyzed. Ears were frozen shortly after the collection and placed in a buffered 10% formalin solution. All ears were scanned by the nuclear magnetic resonator (NMR) (Bruker Bio Spin AVANCE 400WB) to measure the cochlear configuration. The ears were decalcified in 5% formic acid for three weeks and processed into slides 10-μm cryosections by the Kawamoto film-sectioning method (Cryofilm transfer kit; *Leica* Microsystems) (Kawamoto 2003). Every 10th section was stained with hematoxylin and eosin and mounted. Basilar membranes were shown by a laser scanning microscope Olympus Model FV1000 at a

×10 (width) × 20 (thickness) objective magnifications with a scale and ocular calibrated scale for measurements. The basilar membranes were measured for width and thickness using ImageJ (National Institutes of Health, USA. Ver.1.43.).

3 RESULTS

3.1 *Characteristics of the HF underwater noise*

Underwater noise of the HF was a “broadband” sound with energy spread continuously over a range of frequencies.

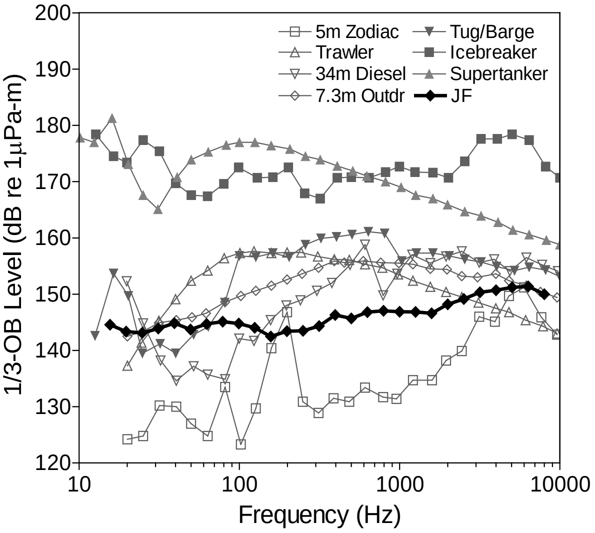

Figure 1. Estimated 1/3-octave source levels of underwater noise (at 1m) of the HF and other vessels summaries of Richardson *et al*.(1995).

Source levels at 1m were estimated by cylindrical spreading transmission loss TLc = 10log r (dB) and absorption loss (Francois & Garrison1982) with distance from source (100m), water depth (88.8m), water temperature (19°C), salinity (35‰), pH (8). As a result, the estimated source level was 146.3±2.6 dB *re* 1μPa-m(Mean±SD) with peak sound level of 151.4 dB *re* 1μPa-m at 6,300Hz. The sound level of the HF was almost equal to that of small ships (Fig.1).

3.2 *Assessing audibility by measuring of vocalization*

48 biological sounds estimated to be emitted by Bryde’s whale were recorded during a total of 8h24m15s recording time. We judged whether sounds were emitted by Bryde’s whale based on the following two points, 1) any marine animals other than Bryde's whale were not visually-observed during recordings, 2) these sounds showed similarities to Bryde’s whale vocalizations described by Oleson et al. (2003). These sounds were assigned to two categories: a) swept tonal call, b) harmonics call (Fig.2).

1 Swept tonal call [Fig.2(a)] was detected 46/48 calls. Table 1 indicates a summary of the quantitative parameters of this call type. These calls were tonal and frequency modulated sounds characterized by an arch-like structure and no repetition. The mean peak frequency of these calls was 269.9Hz±71.3 (mean±SD) ranging from 131.6Hz to 373.4Hz. The mean duration for this call type was 0.71 s±0.30 (mean±SD). This type calls were first recorded off the coast of Japan.

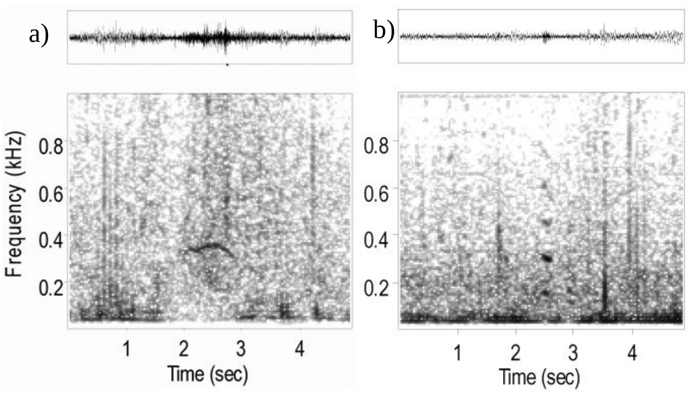

Figure 2. Envelope curves and spectrograms of two phrase types attributed to Bryde’s whales in Japan. (a) Swept tonal call (b) Harmonics call. Both spectrograms were made with a 512-point FFT, 75.0% overlap, and Hamming window.

2 Harmonics call [Fig.2 (b)] was detected only 2/48 calls in this study. The calls included higher-frequency harmonics [fundamental frequency 78.5(74.0-83.0) Hz] than these reported by Oleson *et al.* (2003) (approximately 45Hz). The mean of duration for this call type was 0.28 (0.17-0.39) s.

A total of 12547 clicks of sperm whales were recorded during a total of 7h20m23s recording time (Fig.3). Table 1 indicates a summary of the quantitative parameters of clicks. The peak frequency of the clicks was 3174Hz (geometric mean, 95% Cl 3140-3208). The duration of the individual pulses within a click is 9.27±0.05ms(Mean±SD). The recorded levels of the clicks were approximately 150 dB *re* 1μPa.

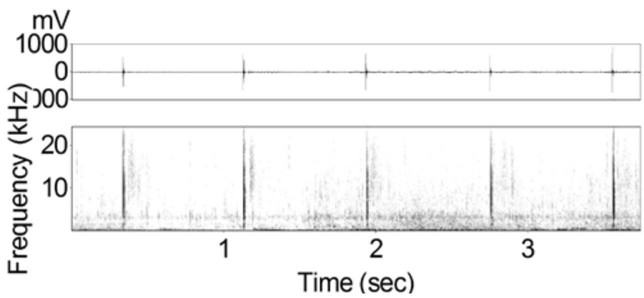

Figure 3. Envelope curves and spectrograms of the clicks of sperm whales. Spectrograms were made with a 512-point FFT, 75.0% overlap, and Hamming window.

Table1. Frequency quantitative parameters for vocalization.

Species (Whale)	Sound type	Frequency Range(Hz)	Peak Frequency(Hz)
Bryde's whales	Swept tonal call (n=46)	131.6-373.4	269.9±71.3 (Mean±SD)
	Harmonics call (n=2)	250.0-293.0	271.5 (Mean)
Sperm Whales	Clicks (n=12581)	1870-4780 (3140-3208)	3174 (GM, 95% Cl)

3.3 *Anatomical Predictions of the audible range*

Initial surveys of cochlear dimensions from NMR images showed that common mike whales cochlear were type M while Baird's beaked whales cochlear were type II (Ketten 2000) (Fig.4a). Furthermore we measured the cochlea length and other cochlea configurations shown in Table 2. It took approximately 3 weeks to complete decalcification of the cochlear. The Kawamoto film-sectioning method allowed the best preparation of thin sections from specimens of the cochlear (Fig 4b). All specimens had measurable intact basilar membranes in apex and base region of the cochlea(Fig 4c). Table 2 shows the thickness/width ratios and estimated frequency of the audible range for each species from the data using the model described in Ketten (2000).

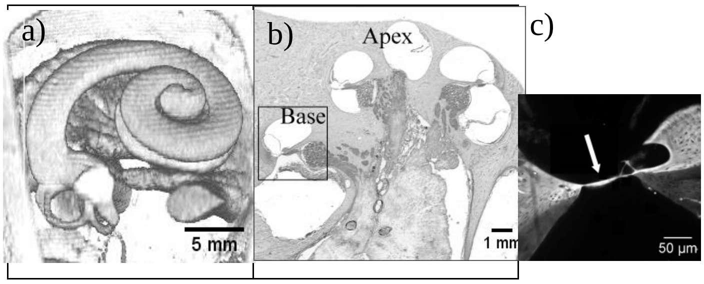

Figure 4. Images of cochlea from Baird's beaked whales. a) A three-dimensional reconstruction by NMR. b) Images from histology slide preparations. c) The basilar membrane(arrow) of the cochlea basal turn (20×)

Table 2. The cochlear spiral and the basilar membrane measurements, and predicted frequency of the audible range from the measurements [the model described in Ketten (2000)].

Species	Common minke whales (n=9, 9individuals)	Baird's beaked whales (n=6, 3individuals)
Number of turns	2.32(±0.09)	2.08(±0.09)
Membrane Length(mm)	54.82(±2.20)	54.44(±2.35)
Basal diameter (mm)	12.36(±0.83)	16.14(±2.35)
Axial height (mm)	7.36(±0.55)	7.66(±1.09)
Membrane Thickness Base/Apex (µm)	9.0/5.4	15.9/13.5
Membrane Width Base/Apex (µm)	171.4/1128.0	142.4/304.5
T/W ratio Base/Apex	0.0525/0.0098	0.1568/0.020
Predicted Frequency (kHz)	15.93/0.12	33.09/0.27

4 DISCCUSION

Large cetaceans response to sound level higher than from 110 to 170dB *re* 1µPa (Richardson *et al* 1995), and it requires 170dB re 1µPa to trigger a strong reaction when they are away from the source (Akamatsu 1993). Since the HF cruising sound level at 100m from source had 126.3dB *re* 1µPa (source level 146.3 (±2.6) dB *re* 1µPa-m) was probably too low to make whales react to the sound. In addition, peak frequency of the HF may be higher (6.3 kHz) than sensitive hearing of large cetaceans. Therefore, it is necessary to install the UWS that effectively produces sounds that make whales recognize the approaching the HF.

Because it is to correspond the dominant frequencies of the vocalization to the most sensitive region of receptor system in vertebrate taxa (Green and Marler 1979), the present study assessed the dominant audible ranges for each whale as follows; Bryde's whales 0.1-0.4kHz, sperm whales1.9-4.8kHz.

Alternatively, an anatomical structure of inner ear correlates to the maximal and minimum frequency of the audible range in each cetacean species (Ketten and Wartzok, 1990). Therefore the audible ranges for each whale were predicted as follows; common minke wahles: 0.1-15.9kHz and Baird's beaked whales:0.06-33.1kHz.

Thus, it is considered that the existing the UWS (6-20kHz) is necessary to be modified to produce the lower frequency down to less than 15.9kHz for common minke whales, to less than 0.4kHz Bryde's whales, and between 1.9 to 4.8kHz for sperm whale.

As for Baird's beaked whales, predicted audible rangea are well inside of those by the existing UWS. However the vocal frequency for Bryde's whales is fur below of to lower band by the UWS. The gaps are thought to be technically difficult to fill up. Because the frequency of vocalization is certainly within the audible range and the practical audible range is much wider, this must be investigated by further examination through anatomical approach mention above.

For further study, it is necessary to improve the acoustic property of the UWS based on the sound known to have a repellent effect against large cetaceans within the frequency range shown in this study.

5 CONCLUSION

The HF noise level was probably too low to make whales react. Therefore, it is necessary to install the UWS effectively. Based on vocalizations and anatomical observation, it is considered that the existing the UWS (6-20kHz) is necessary to be modified to produce the lower frequency down to less than 15.9kHz for common minke whales, to less than 0.4kHz Bryde's whales, and between 1.9 to 4.8kHz for sperm whale.

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