TRANSNAV
http://www.transnav.eu
the International Journal on Marine Navigation and Safety of Sea Transportation
Volume 9
Number 2
June 2015

DOI: 10.12716/1001.09.02.08

Development of the Effective Underwater Speaker Sound Modulated by Audible Sound Frequency Range of Large Cetaceans for Avoidance with Ship Collision

H. Yamada, N. Kobayashi, T. Nakashima & H. Kato
Tokyo University of Marine Science and Technology, Tokyo, Japan

ABSTRACT: The underwater speaker (UWS) has been installed on high speed vessels; hydrofoils (HF) with low-noise during their cruises, to avoid sudden collisions with large cetaceans, while its performance has remained uncertain because of the problem in quality of the produced sound. Thus, we developed a sound source for the UWS by modulating the sound based on the audible range of major large cetaceans so as to increase its utilities. To investigate the audible sound frequency range of cetacean, we tried two procedures, (1) indirect-estimation from relationship between cetaceans audibility and vocalization, and (2) indirect-estimation from measurements on the cochlear basal membrane. We also synthesized the two new sound sources which we can potentially expect an avoidance with large cetaceans. Through several field experiments with deploy the new sounds we reached a tentative conclusion that the new sound was effective in terms of inducing the cetaceans' avoidance reaction and would be also expected to be applied to other low-noise vessels. (Patent applied for, JP2014-171411)

1 INTRODUCTION

The hydrofoil (HF) is super high-speed vessels and is an important vessel in Japan that connects the remote islands with the mainland for shorter travel time than that of ferry and is superior in seaworthiness. However, in recent years the accidents of the collision between HF and large cetaceans have occurred and immediate correspondence to avoid the accident is required. 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), the sound level was assumed to be probably too low to make cetaceans react to the sound (Yamada *et al.*2012).

The Under Water Speaker (UWS) has been installed on the HF for avoiding the collisions with large cetaceans. However, its effectiveness is still uncertain. Thus, it is the most important measure to improve effectiveness of the current UWS in terms of issue of collision avoidance. In this study, for the purpose of collision avoidance of large cetaceans and HF, the following three studies were made in order to develop the new sound of UWS.

1 We adjusted the UWS sound to the audible range of causal cetaceans on HF route.
2 We developed the new sound by synthesizing sound potentially has cetaceans repellent.
3 We demonstrated acoustic properties of the new sound produced from the UWS of the cursing HF.

2 ADJUSTMENT OF THE UWS SOUND TO THE AUDIBLE RANGE OF CAUSAL CETACEANS

For development of the effective UWS sound, it is most important to identify the sound frequency to effectively repel cetaceans. Therefore, it is necessary to identify the audible frequency range of cetacean species which is considered to cause the collision with vessels. 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 indirectly by the following two procedures, (1) indirect-estimation from relationship between cetaceans audibility and vocalization, and (2) indirect-estimation from measurements on the cochlear basal membrane. It 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). 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).

Shakata *et al*. (2008) and Tsuji *et al*. (2013) identified sperm whale (*Physeter macrocephalus*), Baird's beaked whale (*Berardius bairdii*), common minke whale (*Balaenoptera acutorostrata*), Bryde's whale (*Balaenoptera edeni*) and humpback whale (*Megaptera novaeangliae*) as possible causal species of the collision on the sea route of the HF in Japanese water. The vocalization frequency range were made reference to previous research of sperm whale in the southeastern coast of Chichijima, the Bonin (Ogasawara) Islands of Japan and Bryde's whale in the waters of Kochi on the south western coast of Japan (Yamada *et al*. 2012) and humpback whale in the Ryukyu region of Japan (Maeda *et al*. 2000).This study estimates the audible range of sperm whale beaked whale by describing the anatomy used the Kawamoto film-sectioning method (Kawamoto 2003) of their inner ears and applying the model described by Ketten (2000) extended Yamada *et al*. 2012 data of common minke whale and Baird's beaked whale (Table 1).

However, since the maximum sensitivity of the current UWS is 8kHz-30kHz, sound pressure of frequencies below 8kHz characteristic tends to decrease. Therefore, considering the maximum sensitivity of the speakers hardware, the frequency of the new UWS sound was set at 5kHz, the maximum dominant audible frequency of the sperm whale and the humpback whale that pose a particularly high collision risk (Kato *et al*. 2012), which is a downward shift by 1kHz from the currently used frequency range of 6-18kHz.

As far as the Bryde's whale is concerned, the challenge lies in how to infer its audible frequency range using the anatomical predictions since its dominant audible frequency is significantly lower than the frequency of the new UWS sound. However, given that the audible range of the common minke whale, which belongs to the same family, is 0.12-15.93kHz, it is extrapolated that 5kHz might be fit well within the audible range of the Bryde's whales.

3 SYNTHESIZING OF NEW SOUNDS FOR THE EFFECTIVE UWS

Using or synthesizing a potential repelling sound for cetaceans would be effective for making large cetaceans avoidance from HF. For example, Watkins (1986) reported that cetaceans often react to sudden or loud sounds of vessel, such as from an engine starting, a close approach, changes in direction, putting engine in and out of gear, and propeller cavitations during reverse or sharp turns. We synthesized the two sound sources in order to install the UWS 1) diesel engine ship noise of the Japanese whale research vessel 2) the clang sound produced by hitting the metal pole with a hammer, which we can potentially expect an avoidance with cetaceans. It is described below in detail about the two sounds that were used in the synthesis.

1 Ship noise whale research vessel: We used a high-pass filter with 0.12 kHz for cruising noise at the time of the maximum speed (16.7kt, 200rpm) by the Japanese whale research vessel Yushin Maru No.2 (747t , 69.6m, Owned by Kyodo Senpaku Co.,Ltd.) with 2 cycle slow-speed diesel engine.
2 The clang sound produced by hitting the a metal pole: We recorded clanging sound by hitting a metal pole in the water and adjusted the frequency and sound interval. For frequency, we modulated 2.00 kHz as an original sound to 5.00 kHz, 8.00 kHz, and 10.00 kHz, and then alternately arranged 3 frequencies of the clanging sound. This frequency was adjusted with the maximum frequency of dominant audible frequency by causal cetaceans and the maximum speaker sensitivity. In addition, for the sound interval, we also modulated 0.52 second of the original sound to approximately 0.09 second in accordance with the interval of whaling vessel's diesel knocking sound. The spectrograms and frequency characteristics of the synthesized sound source are shown in figure1 and 2. The frequency characteristic was assessed by 1/3-octave bands analysis using Avisoft SASLab Pro (Avisoft Bioacoustics, Germany.Ver.5.2.) because sound levels in 1/3-octave bands are useful in interpreting noise effects on animals.

Table 1. Summary of audible range of causal cetaceans.

	Species	Dominant audible range by vocalization (kHz)	Audible range by Anatomical predictions (kHz)
Odontoceti (toothed whales)	Sperm whale	1.87-4.78 (Yamada et al.2011)	0.29-47.75
	Baird's beaked whale		0.27-33.09 (Yamada et al.2011)
Mysticeti (baleen whales)	Common minke whale		0.12-15.93 (Yamada et al.2011)
	Baird's beaked whale	0.13-0.37 (Yamada et al.2011)	
	Humpback Whale	0.03-4.80 (Maeda et al.2000)	

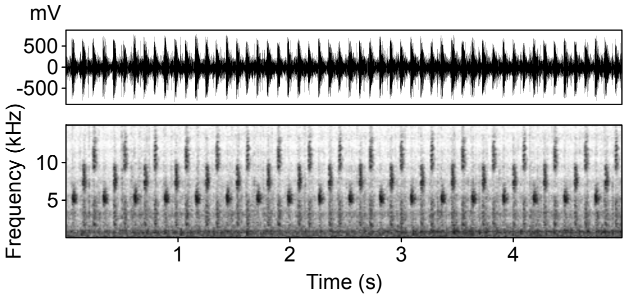

Figure 1. Envelope curves (above) and spectrograms(below) of the new UWS sound source. Spectrograms were made with a 1024-point FFT, 75.0% overlap, and Hamming window.

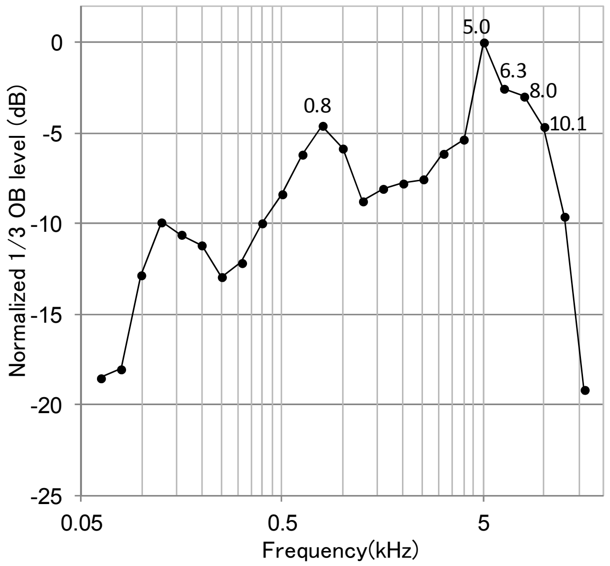

Figure 2. The 1/3 octave-band spectrum measured of the new UWS sound source. Filter: ANSI S1.11-2004 standard.

The characteristic of the new sound source would be using a potential repelling sound for cetaceans and synthesizing audible frequency for whales with collision risk (Patent applied for, JP2014-171411).

4 THE EFFECTIVE RANGE OF THE NEW UNDERWATER SPEAKER SOUND

It is necessary to evaluate whether such frequency characteristic and sound pressure can evoke response by cetaceans when we playback the new UWS sound through HF speakers during the cruise. Therefore we recorded the new sound playbacked from HF during its cruise at service speed (38-39kn) from a small vessel at a distance of 150-163m. Recordings were made using a Aqua Sound model AQH-020 (frequency response 20Hz to 20kHz) omnidirectional hydrophone has sensitivity of approximately -193dB re 1V/μPa with 10m cable. It was connected via pre-amplifiers, on a Sony PCM-D50 digital recorder (16bit 44.1 kHz). The estimated source levels of underwater noise (at 1m) of the HF were calibrated by Transmission Loss and Absorption Loss (Francois & Garrison1982).

As a result, the frequency characteristic indicated a peak frequency at 5.0kHz, 6.3 kHz, 8.0kHz, and the sound below 8kHz as the maximum speaker sensitivity was also reproduced (Fig.3).

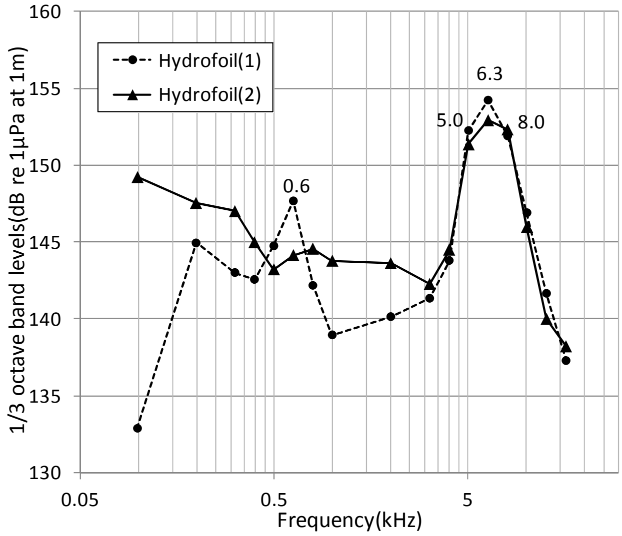

Figure 3. The 1/3 octave-band spectrum measured of the playbacks new UWS sound source from the two types operational HF.

The frequency range overlapped with audible range of cetaceans has been expanded since a lower frequency as 5kHz was added to the present UWS frequency range (6, 10,14,18kHz).

For the evaluation of response-evoking distance (the effective range), we have successively recorded a sound pressure change of the new UWS sound source reproduced from JF as closing to a recording point. The reference for the effective range sound pressure was set as being higher than the lowest sound pressure 102dB re 1μPa (Frankel *et al.*1995) with a response of the Humpback whale and also set a point with a constant 102dB as the effective range. Furthermore, the effective range was calculated by trigonometric function with distance/time at the time of the closest approach, vessel speed, and time coefficient at 102dB.

The effective range $(X^2) = (a^2) \times (b^2)$

a：Closest distance to the HF

b：vessel speed×(Closest time - time coefficient at 102dB)

As a result, we found that it was reproduced by response-evoking sound pressure of cetaceans from the average distance 389.8m (max 459.4m/min 294.2m).

Table 2. The effective range of the new UWS sound.

#	(A)Time coefficient at 102dB(s)	(B)Closest time to the HF(s)	(B)-(A) (s)	Closest distance to the HF(m)	The effective range(m)
1	01′38″	01′58″	20	150	459.4
2	15′32″	15′44″	12	150	294.2
3	01′55″	02′13″	18	163	415.7

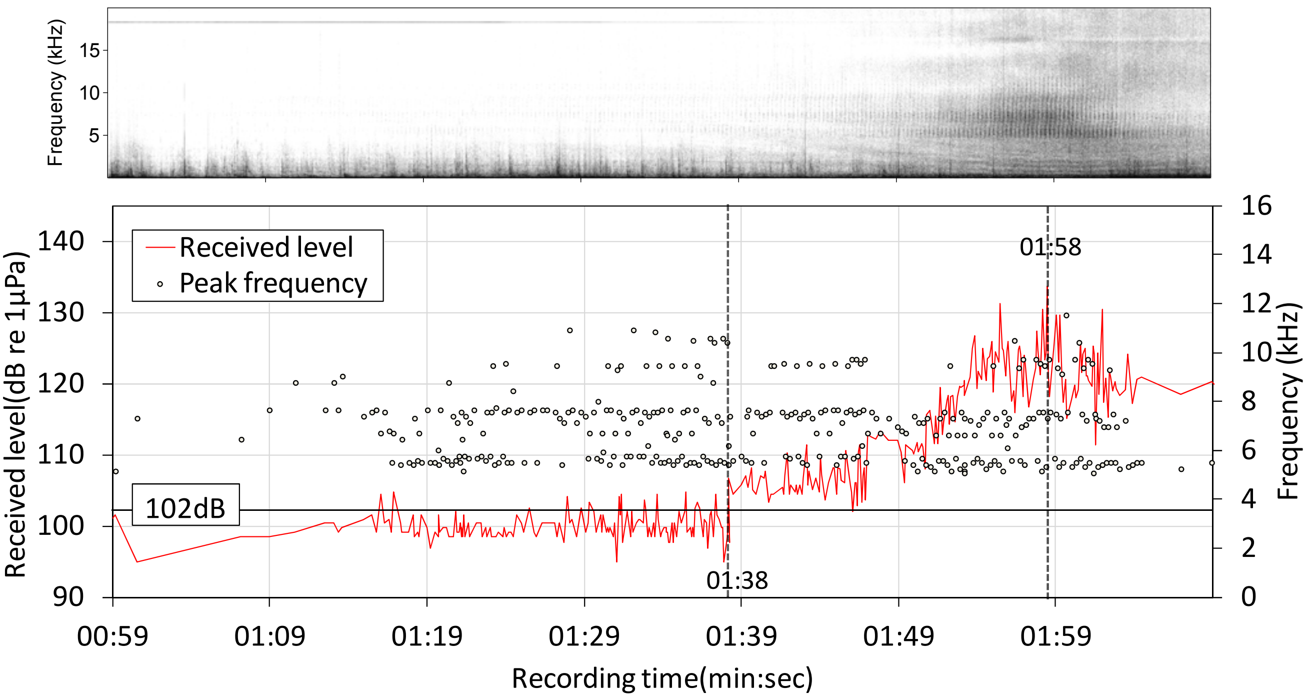

Figure 4. A sound pressure change(a red line) and peak frequency(outlined circles) of the new UWS sound source reproduced from HF as closing to a recording point (below).Spectrograms were made with a 1024-point FFT, 0% overlap, and Hamming window(above).

This distance was longer than approximately over 140m which would be a distance to an obstacle as a condition where water landing/emergency-stop ship maneuvering should instantly be taken by automatic control when a HF finds any obstacles at 46 knots (Yagi 1991). In addition, when Kagami (2011) conducted questionnaire survey for HF officers, she found that a collision could be avoided if an emergency water landing is made with a distance of 100m or longer; therefore, it can be said that ship officers will have enough distance to avoid such collision if it is reproduced with the effective range of cetaceans from the minimum distance of 294m. On the other hand, it was discussed whether how cetaceans responded to the new sound source and how it evoked a repellant behavior toward cetaceans, but such issue was examined by Nakashima *et al.* (2015) submitted to the same volume as the separate dedicated paper.

5 CONCLUSIONS

The study made an improvement for the UWS sound source in terms of collision-avoidance between HF and cetaceans. The improvement was carried out on the basis of aural characteristic of cetaceans and the frequency adjustment with 5kHz, 8.00kHz, and 10.00kH. Furthermore, 2 sounds were synthesized as a potential repelling sound for cetaceans. When the new sound source created in the study was actually playbacked from HF during the cruising, it was reproduced by response-evoking sound pressure of cetaceans from the average distance of 390m; therefore, we concluded this distance could be enough distance to avoid a collision by HF officers. A development of the new UWS sound source aimed at a collision-avoidance with cetaceans while adjusting dominant audio frequency of cetaceans for a risk of collision and using a potential repelling sound for cetaceans. In fact, it was examined by Nakashima *et al.* (2015) how the new UWS sound source would evoke a response by cetaceans. The new UWS sound would be also expected to be applied to other low-noise vessels like a yacht.

ACKNOWLEDGMENT

We would like to special thank for supporting for investigation Sado Kisen Co., Ltd. and Kyodo Senpaku Co., Ltd.,. Key specimens provided by the Institute of Cetacean Research. We wish to thank the help given by Dr.Okanoya of Tokyo University and Dr.Kawamoto of Tsurumi University in analyzing. Thanks to Laboratory of Maine Biology, Tokyo University of Marine Science Technology, particularly grateful for the assistance given by Kimika Tsuji and Kazuya Kitayama. This work supported by Kawasaki Heavy Industries Co.,Ltd and KHI JPS Co., Ltd.

REFERANCES

Echteler, S.W., Fay, R.R & Popper, A.N. 1994. Structure of the mammalian cochlea. In: A.N. Popper.(eds), *Comparative hearing: mammals* :134-171.New York. Springer-Verlag. Press.

Francois, R.E. & Garrison, G. R. 1982. Sound absorption based on ocean measurements: Part I: Pure water and magnesium sulfate contributions. *Journal of the Acoustical Society of America*. 72(3): 896-907.

Frankel, A.S., Mobley, J.R. & Herman, L.M., 1995. Estimation of auditory response thresholds in humpback whales using biologically meaningful sounds, In Kastelein R.A., Thomas J.A., Nachtigall P.E. (eds), *Sensory Systems of Aquatic Mammals*:55-70.Woerden: De Spil Publishers.

Green, S & Marler, P. 1979. The analysis of animal communication. In: P. Marler & J.G. Vandenbergh. (eds), *Social behavior and communication, vol 3. Handbook of behavioral neurobiology*: 73-158. New York. Plenum Press.

Kagami, L. 2011. Fundamental research of collision avoidance between large cetaceans and super high speed vessels - Analysis for the occurrence of cetaceans on the sea routes and early detection system of cetaceans. *Master thesis, Tokyo University of Marine Science and Technology.* :1-105.

Kato, H., Yamada, H., Shakata, K., Odagawa, A., Kagami, L., Yonehara, Y., Terada, M., Sakuma, K., Mori, H., Tanaka, I., Sugioka, H. & Kyo, M. 2012. Towards Safer Navigation of Hydrofoils: Avoiding Sudden Collisions with Cetaceans. *International Journal on Marine Navigation and Safety of Sea Transportation.* 6(1):143-147.

Kawamoto, T. 2003. Use of new adhesive film for the preparation of multi-purpose fresh-frozen sections from hard tissues, whole-animals, insects and plants. *Arch. Histol. Cytol* .66(2):123-143.

Ketten, D.R & Wartzok, D. 1990. Three-dimensional reconstructions of the dolphin ear. In: R. Kastelein.(eds), *Sensory abilities of cetaceans.* :81-105.New York: Plenum Press.

Maeda, H., Koido, T. & Takemura, A. 2000. Principal component analysis of song units produced by humpback whales (*Megaptera novaeangliae*) in the Ryukyu region of Japan. *Aquatic Mammals.* 26(3):202-211.

Nakashima, T., Kobayashi, N., Yamada, H., Katsumata, T., Yoshida, R., Okabe, H., Kawazu, I., Yanase, Y., Omine, M., Terada, M., Sugioka, H., Kyo, M. & Kato, H. (submitted to TransNav2015). Repellent effect of the new UWS sound against large cetacean Repellent effect of the new UWS sound against large cetacean.

Shakata, K., Odagawa, A., Yamada, H., Matsunaga, H., & Kato, H. 2008. Toward to avoiding ship strike of cetaceans with the high-speed HF(1)-Identifying expected cetacean species on the track lines of HF. *2008 Annual meeting of M.S.J. summary* :135.

Tsuji, K., Kagami, L., Shakata, K. & Kato, H. 2014. Circumstantial Analysis of the Appearance of Whales on the Hydrofoils Route in the Japanese Coast. *The Journal of Japan Institute of Navigation.* 130(0):105-113.

Watkins, W.A. 1986. Whale reactions to human activities in Cape Cod waters. *Marine mammal science.* 2:251-262.

Yagi, T. 1991. Night navigation of the Jetfoil, report of the safety navigation of super high speed vessels. *Passengerboat.* 177:10-18.

Yamada, H., Kagami, L., Yonehara, Y., Matsunaga, H., Terada, M., Takahashi, R., Okanoya, K., Kawamoto, T. & Kato, H. 2012. Estimation on Audibility of Large Cetaceans for Improvement of the Under Water Speaker. *International Journal on Marine Navigation and Safety of Sea Transportation.* 6(4):589-593.