Measurement of Ship Noise in Shallow Sea Area

Tomoki MURAYAMA*

1. INTRODUCTION

In July 2023, IMO/MEPC80 approved a revised version of the non-mandatory circular *Guidelines for the Reduction of Underwater Noise from Commercial Shipping to Address Adverse Impacts on Marine Life,* which include provisions to assist shipowners with the development of underwater noise management plans. In line with this, in October 2023, ClassNK (hereinafter, the Society) issued new guidelines entitled “Guidelines for Underwater Noise from Ships (Edition 1.0) ” (hereinafter, 2023 Guidelines)*1. In addition to measurement of underwater noise from ships in deep waters in accordance with the provisions of ISO 17208-2 specified in the 2023 Guidelines, the ISO is also drafting new provisions, ISO 17208-3, for shallow sea area, where measurement is easier, and an empirical evaluation of that measurement method is underway in the EU’s Saturn Project.

Based on those moves, the Society is now studying a system that considers restrictions unique to Japan, for example, water depth and ocean currents, navigation routes, etc. This article introduces a portion of that study concerning ship noise measurement in Japan’s coastal waters (shallow sea area).

2. NOISE MEASUREMENT IN THE 2023 GUIDELINES

The 2023 Guidelines present details of measurements of ship noise. The measurement conditions are arranged in simple terms in the following.

2.1 Measurement Points (Excerpted from 2023 Guidelines, Section 5.2)

The following two measurement points are specified.

(1) Water depth: 150 *m* or more, or more than 1.5 *times* the length of the ship, whichever is greater.

(2) Sea area where there is no traffic congestion.

* As the reason or setting these points, it can be understood that (1), the maximum wavelength of the generated frequency of noise is considered based on the size of the generation source, and (2), the intention is to ensure the safety of measurements and reduce the effects of background noise on measurements.

2.2 Measurement Conditions (Excerpted from 2023 Guidelines, Section 5.3)

The 2023 Guidelines specify the Beauford scale wind force, wave scale, main engine output, etc.

* It can be understood that the purpose is to grasp the magnitude of the signal levels of the measurement target and background noise during the measurement.

2.3 Measurement Procedure (Excerpted from 2023 Guidelines, Section 5.4)

The following procedure is described.

(1) Measurements are to be conducted by personnel familiar with the use of the equipment.

(2) Only personnel necessary for ship operation and measurement purposes are, in principle, to be allowed on board the ship during the measurement.

(3) Measurement sections are to be in the range of ±30 *degrees* from the center of the hydrophone array.

(4) The number of navigations and measurements is to be twice with the hydrophone array on the starboard side and the port side.

(5) The distance to the Closest point of Approach (DCPA) to the hydrophone array is to be 100 *m* or the ship’s length, whichever is greater.

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* Oki Electric Industry Co., Ltd.

*1 “Guidelines for Underwater Noise from Ships (Edition 1.0)” issued by ClassNK in October 2023.

(6) The hydrophones used in the measurements are to be omni-directional, and are to be the bottom-mounted type, the floating buoy type or the floating line type lowered from a support ship. Three hydrophones are to be used.

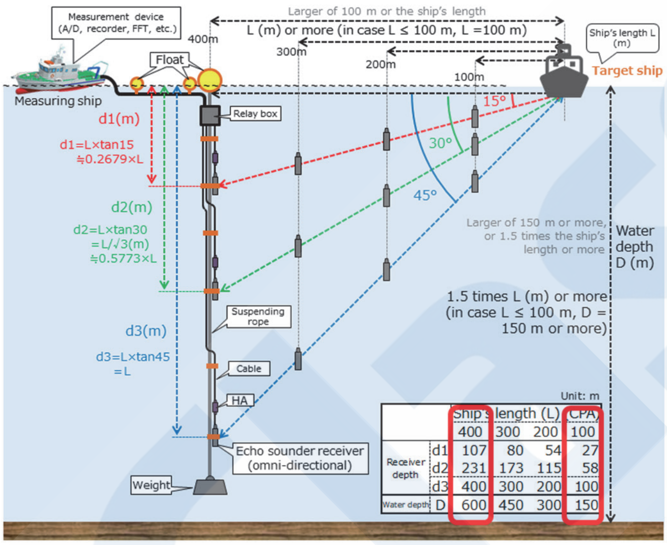
(7) The hydrophones are to be calibrated in advance.

(8) The frequency band is to be 10 *Hz* to 10 *kHz*.

Although the author attempted to extract the key points in the above, these requirements are specified in considerable detail. The following proposes a measurement environment for ship noise measurement in shallow sea area, considering the issues for measurements and their countermeasures, while utilizing these provided measurement parameters.

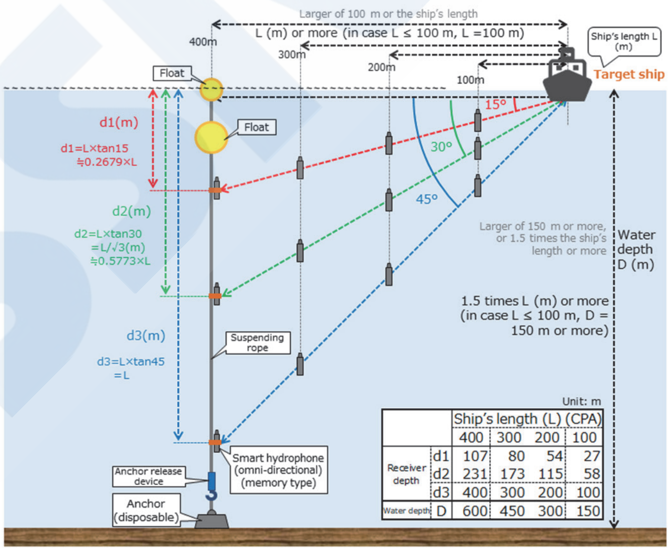
3. TWO METHODS CONSIDERING DIFFERENCES IN THE MEASUREMENT METHODS

Figs. 1 and 2 on the following page show the image of measurements by a floating type hydrophone array and a bottom-mounted type hydrophone array based on the provisions of the Guidelines presented in the above Chapter 2. When the hydrophones are arranged at relative angles of ±30° with respect to the ship being measured (target ship), the guidelines specify that the water depth is to be at least 1.5 times the ship's length. Therefore, assuming the ship's length is 100 m and the water depth is 150 m, a horizontal distance of 100 m from the CPA (Closest Point of Approach) to the measurement system at this time is necessary. Similarly, if the ship's length is 400 m, the required water depth is 600 m and the distance from the CPA to the receivers is 400 m. Considering the distance required to stabilize the ship's speed of movement toward the CPA and turn in order to measure the port side and starboard side, the sea area necessary in the measurement is assumed to be roughly several km^2.



		Ship's length (L) (CPA)			
		400	300	200	100
Receiver depth	d1	107	80	54	27
	d2	231	173	115	58
	d3	400	300	200	100
Water depth	D	600	450	300	150

Fig. 1 Image of measurement by floating buoy type



		Ship's length (L) (CPA)			
		400	300	200	100
Receiver depth	d1	107	80	54	27
	d2	231	173	115	58
	d3	400	300	200	100
Water depth	D	600	450	300	150

Fig. 2 Image of measurement by bottom-mounted type

With the bottom-mounted hydrophone method in Fig. 2, it would also be possible to use a measuring ship, as show in Fig. 1. However, permanent installation is preferrable considering the difficulty of setting and raising and recovering the hydrophone array, and it is more efficient to install optical fiber and electric cables, etc. to nearby land for the measurements and supply of electric power by wire, and carry out the measurements from a land-based measurement station. Since a mooring type array would be installed permanently at sea in this case, and may become an impediment to navigating ships, it would be necessary to restrict entry into the sea area concerned, inform other ships that may use those sea areas, install warning buoys, etc. Moreover, during measurements by either the floating type or the bottom-mounted type, it may also be necessary to deploy a warning vessel, etc., depending on the circumstances.

4. ISSUES IN ACOUSTIC MEASUREMENTS AND THEIR COUNTERMEASURES

4.1 Issue during Measurements

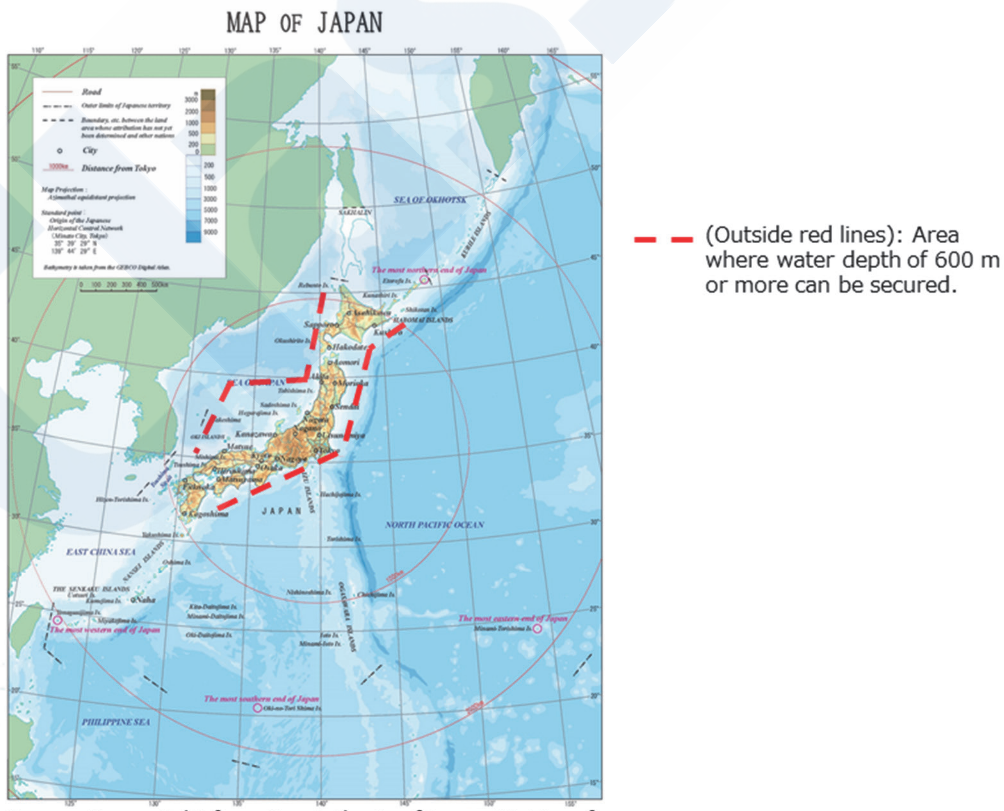
First, let us narrow the candidate sea areas to cases in which the required water depth of 600 m is secured purely for the ship length of 400 m, as described above. In Fig. 3 on the next page, the candidate areas in the seas around Japan are roughly outside the red dotted line. Although cases where ocean trenches exist nearby are excluded, sea areas where measurements are possible cannot be reached without traveling about 100 km from the coast. Moreover, even if the measurement point is reached, the cost of installing and maintaining a permanent bottom-mounted measurement array (shown in Chapter 3, Fig. 2) is easily expected to be enormous. The floating type (Chapter 3, Fig. 1) might be a possible method, but even if it is possible, it can easily be assumed that the cost would increase substantially, considering the entire process from traveling to the measurement area, setting the hydrophone array and preparation for the measurement to completion of the measurement.

This suggests that measurement of ship noise in accordance with the 2023 Guidelines might itself be possible by traveling to waters where the depth is greater than 600 m, but as described above, the measurement scale and the measurement term involved would be prohibitive. Thus, the first issue that can be assumed when envisioning practical use is the fact that “Measurement points are limited to locations that are distant and require excessive time and labor.”

Conversely, let us consider what kind of location and timing of measurements would reduce the burden on ship owners in the operational aspect. First, as the timing of measurements, the time of new ship construction, or the time of maintenance (statutory survey) is considered favorable.

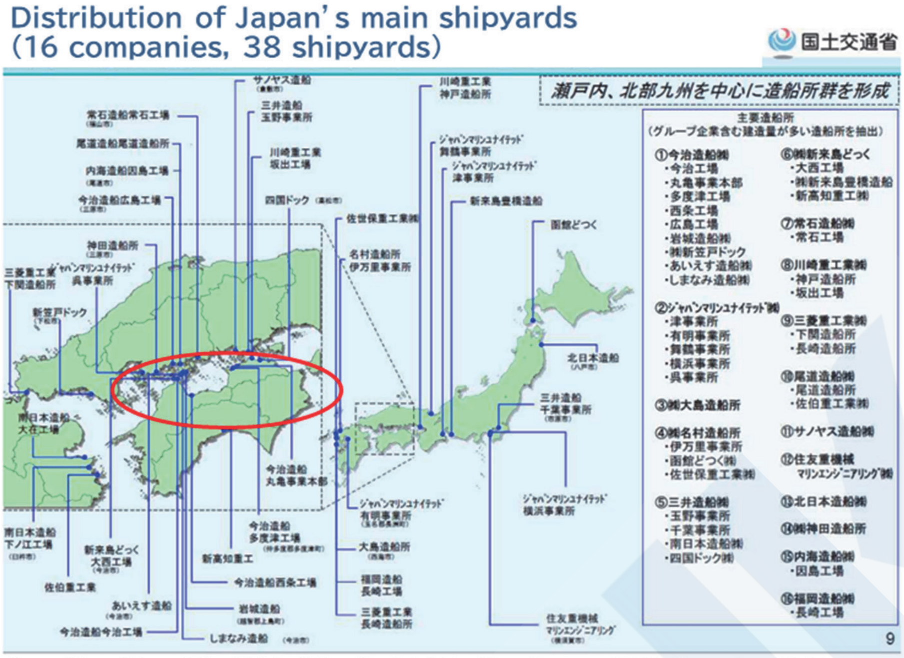
Next, regarding the location, measurement near the shipyard, if possible, would be preferrable, and the Seto Inland Sea, where Japan’s main shipyards are concentrated, was assumed as the operating area. Therefore, let us begin the study of the measurement system based on these conditions. Fig. 4 on the next page shows the distribution of the main shipyards in Japan. If measurements of ship underwater noise are conducted during new building and maintenance (statutory survey), it would be desirable to be able to perform the measurements near these shipyards.

However, as the reader may know, it is difficult to secure even a water depth of 100 m in the Seto Inland Sea, much less the above-mentioned depth of 600 m.



Source: Geospatial Information Authority of Japan, Ministry of Land, Infrastructure, Transport and Tourism (MLIT)

Fig. 3 Water depth in seas around Japan



From "Condition of the Shipbuilding Market," Maritime Bureau, MLIT, December 2017

Fig. 4　Distribution of main shipyards in Japan

In this connection, in the first place, although the 2023 Guidelines require a "water depth of 150 m or more, or 1.5 times the ship's length or more, whichever is greater," let us consider separating this restriction from the technical considerations. First, at a glance, the reason for assuming this in the 2023 Guidelines is that the object of measurement is frequencies of 10 Hz and higher. Since the speed of sound = frequency x wavelength, it seems possible that this might be derived by conversion to a single wavelength of 150 m at the frequency of 10 Hz. However, against the background of the modal theory of propagation, when considering propagation in the horizontal mode, horizontal propagation as such is considered possible even at a water depth of primary mode 37.5 m (= 1/4 wave length = 150 m/4 m). (The propagation cutoff frequency diagram is discussed later in this paper.)

As a second reason for assuming this requirement, since it is desirable to eliminate to effects of sea surface and sea bottom reflections during the measurement, it is possible that the aim was to reduce the effect of sea bottom reflection by lengthening the path route of the bottom reflected waves as much as possible to allow attenuation with distance. However, even if bottom-reflected waves are reduced by securing a certain water depth, it is easy to expect that the influence of interference, including the sea surface reflection route, will remain to a considerable extent if the measurements are made with a single device.

In any case, the second of the above-mentioned issues, that is, the effect of the sea surface and sea bottom reflections, is considered to be extremely large. In view of this, the second real issue for practical implementation is "Constructing a measurement method that minimizes the effect of sea surface and sea bottom reflections in shallow sea area in order to secure measurement locations as close to land as possible." (To restate the first issue initially assumed when envisioning practical use, "Measurement locations are limited to locations that are distant and require excessive time and labor.")

4.2　Proposal of Measurement Method for Shallow Sea Area

The following Fig. 5 shows the images of measurement by the floating buoy method (figures at left and top) and by the bottom-mounted method (right and bottom), assuming Japan's Seto Inland Sea (average water depth: 38 m) as a suitable location. Although it might appear that there is no change from the 2023 Guidelines except that the water depth is 38 m, careful examination shows that the number of hydrophones has been increased from 3 to 5 units. Why is it necessary to increase the number of hydrophones where the water depth is shallower? This reflects the results of a simulation to achieve the aim of "Reducing the effect of interference of sea surface and sea bottom reflected waves" as a measure to solve the above-mentioned problem by the measurement method proposed here. The following presents the results of the simulation and discussion of the influences of multiple wave paths.

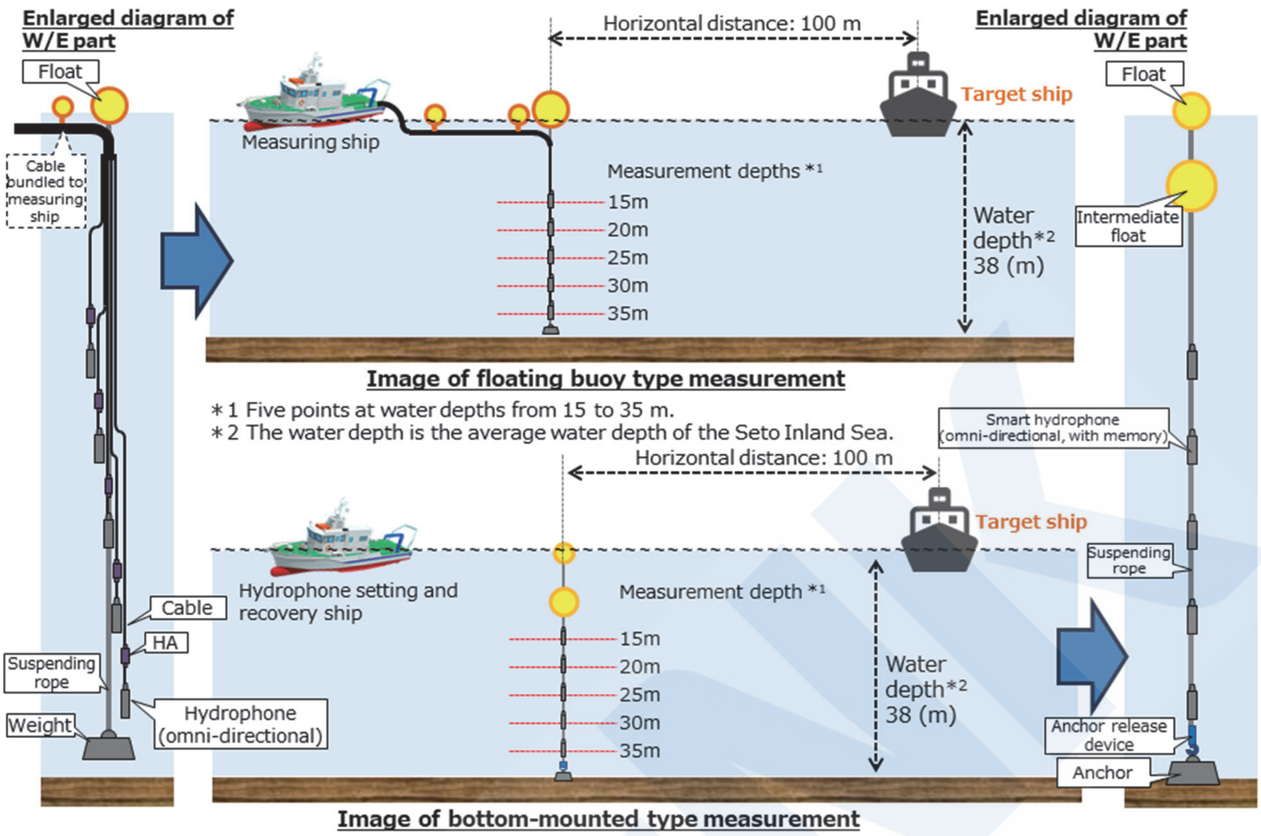


Fig. 5 Image of proposed measurement method for shallow sea area

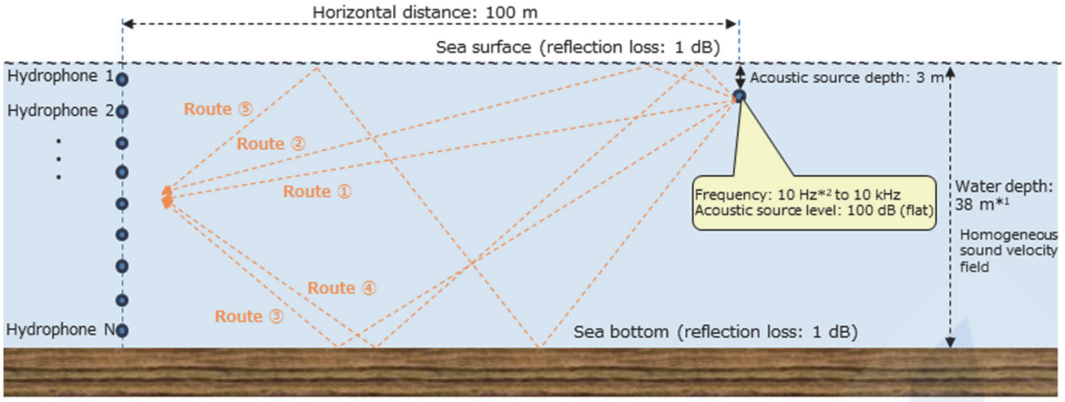
The simulation considered the water depth conditions in two sea areas. One was the average water depth of 38 m in the Seto Inland Sea, and the other was a water depth of 80 m, intended for the Bungo Channel waters, etc.

4.2.1 Study of Sea Area in Seto Inland Sea (Average Water Depth 38 m)

Fig. 6 shows the content of the simulation of acoustic wave interference under a multiple wave path environment in the Seto Inland Sea (average water depth: 38 m).

The figure shows the condition of multi-path interference at each water depth with fine division of the hydrophone water depth. The depth of the acoustic source is 3 m, and the interference results were calculated by considering the propagation condition to be spherical diffusion, for the 5 acoustic paths: ① Direct wave, ② sea surface single reflection route, ③ sea bottom single reflection route, ④ sea surface (forward) single reflection, sea bottom (back) single reflection route and ⑤ sea bottom (forward) single reflection, sea surface (back) single reflection route. Reflection loss was set a 1 dB for both sea surface and sea bottom reflection.

The small figure at the bottom right in Fig. 6 shows that the lower limit frequency (mentioned previously as an item to be discussed later) was achieved at the water depth of 38 m, even for 10 Hz, based on the cutoff frequency of a space enclosed by a rigid body (source: Fundamentals and Applications of Marine Acoustics).



*1 Water depth: Average water depth of the Seto Inland Sea.
*2 Lower limit frequency: Cutoff frequency of space enclosed by a rigid body (see figure below).

Number of reflections of routes ① to ⑤

	Surface reflection	Bottom reflection
Route ①	0	0
Route ②	1	0
Route ③	0	1
Route ④	1 (forward)	1 (back)
Route ⑤	1 (back)	1 (forward)

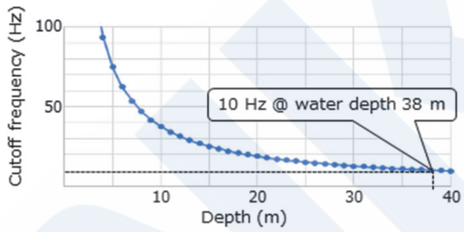


Fig. 6 Conditions of multi-path simulation (average water depth of Seto Inland Sea: 38 m)

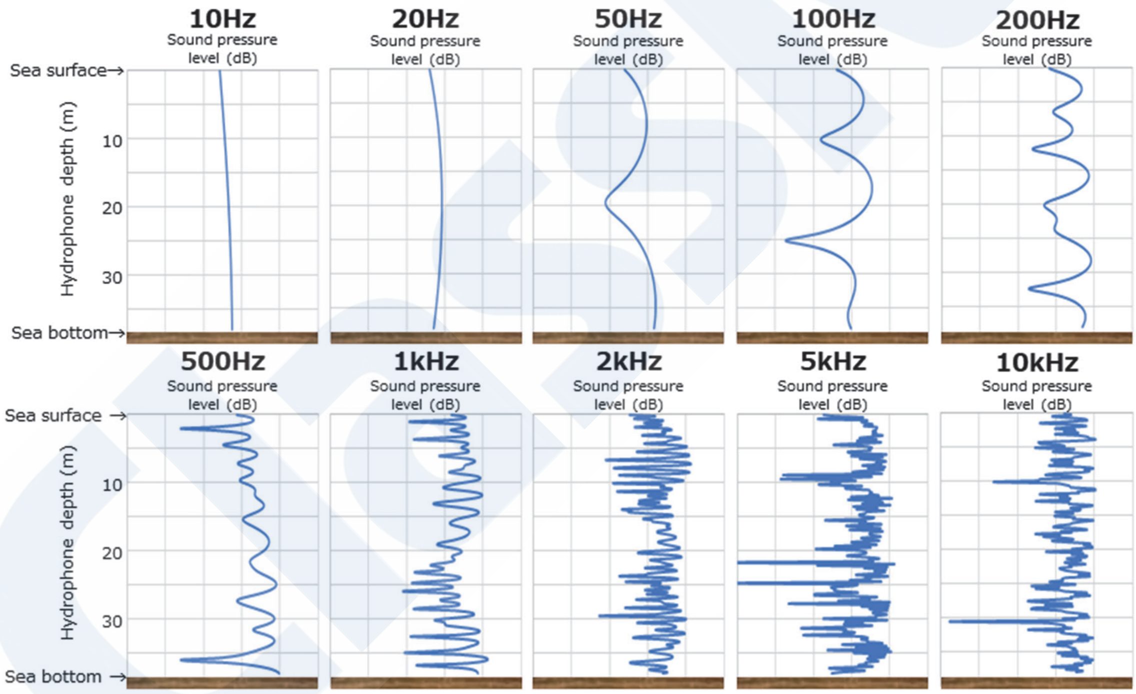


Fig. 7 Changes in level by multi-path interference by frequency at each hydrophone depth

Fig. 7 shows the results of the changes in the sound pressure level by addition of the multiple paths during fine division of the depth from the sea surface to the sea bottom when the hydrophone depth was plotted against frequency under the conditions in Fig. 6. From these results, the following two points can be mentioned: “① The amount of change differs with the frequency, but since the influence of interference varies due to the differences in the multi-path routes depending on the hydrophone depth, and large changes occur in the sound pressure level (although this also depends on the frequency), measurement with only one hydrophone is not desirable,” and② “Receiving the peaks and valleys of changes in the sound pressure level without differentiation by using multiple hydrophone and taking the average sound pressure level is a satisfactory method.”

Here, just to be sure, the principle of level fluctuation due to interference is presented.

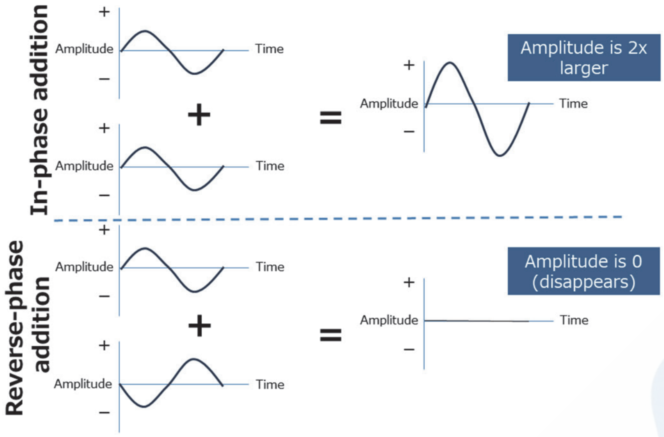


Fig. 8 Situation of in-phase addition and reverse-phase addition of 2 hydrophones

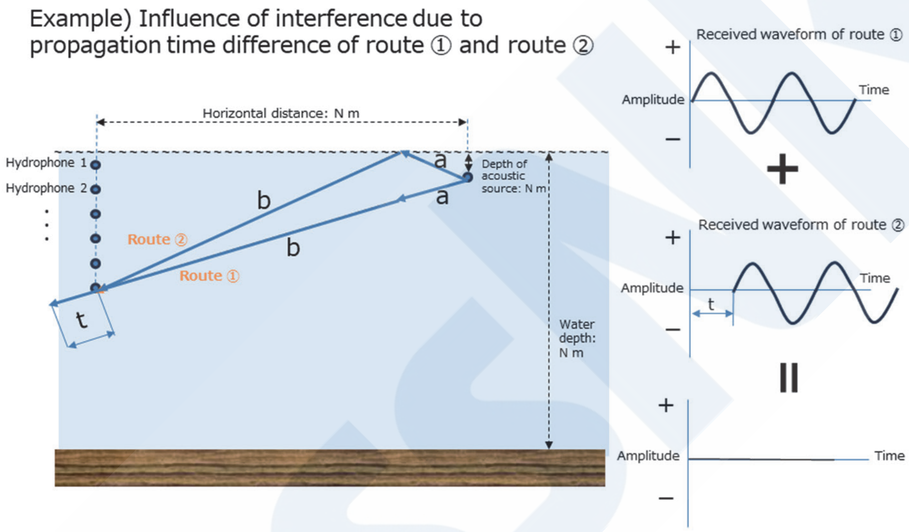


Fig. 9 Situation of addition of 2 waves with different routes
(case when delay time is equivalent to 1/2 of the wavelength, resulting in reverse-phase addition)

Fig. 8 shows extreme examples in which two waves interfere and (top) the sound pressure level after addition increases by 2 times, and (bottom) the waveforms are mutually cancelling and the amplitude becomes 0 (waves disappear).

Fig. 9 shows an example of the two waves in Fig. 8 with interference between a direct wave (route ①) and a sea surface-reflected wave (route ②). If the delay time t of the reflected wave is an integral multiple of the wavelength and the two waves are in phase, and excluding the attenuation of the sea surface reflected wave and attenuation of due to the route length, this is a case of perfect in-phase addition, and the sound pressure level doubles. Conversely, as an example of attenuation, if the delay time t of the reflected wave shifts further by the equivalent of 1/2 of the wavelength against the integral multiple of the wavelength, the two waves are mutually cancelling. Assuming there is no difference in the attenuation of the surface reflected wave and attenuation due to differences in the route length, the two waves have perfectly reversed phases, and the signals disappear due to mutual cancellation.

As a simple method for reducing the influence of these forms of interference, smoothing by using multiple hydrophones in the depth direction is effective.

(*As another measure for reducing the influence of sea bottom and sea surface reflection, use of a directional measurement array may be mentioned. However, particularly at low frequencies, it is difficult to obtain directivity because it is not possible to make an acoustic opening, and directivity requires a large increase in the system scale. Therefore, this paper considers smoothing operation using multiple hydrophones, as this is thought to be the simplest and most effective approach.)

Here, I would like to plot the fluctuations in the sound pressure levels of the hydrophones at each depth side-by-side (Fig. 7), consider “the disruption of the measurement results,” and propose examples of installation of the hydrophones in the depth direction. The situation of interference by frequency depending on the hydrophone installation depth is also shown again, plotted horizontally, in Fig. 10.

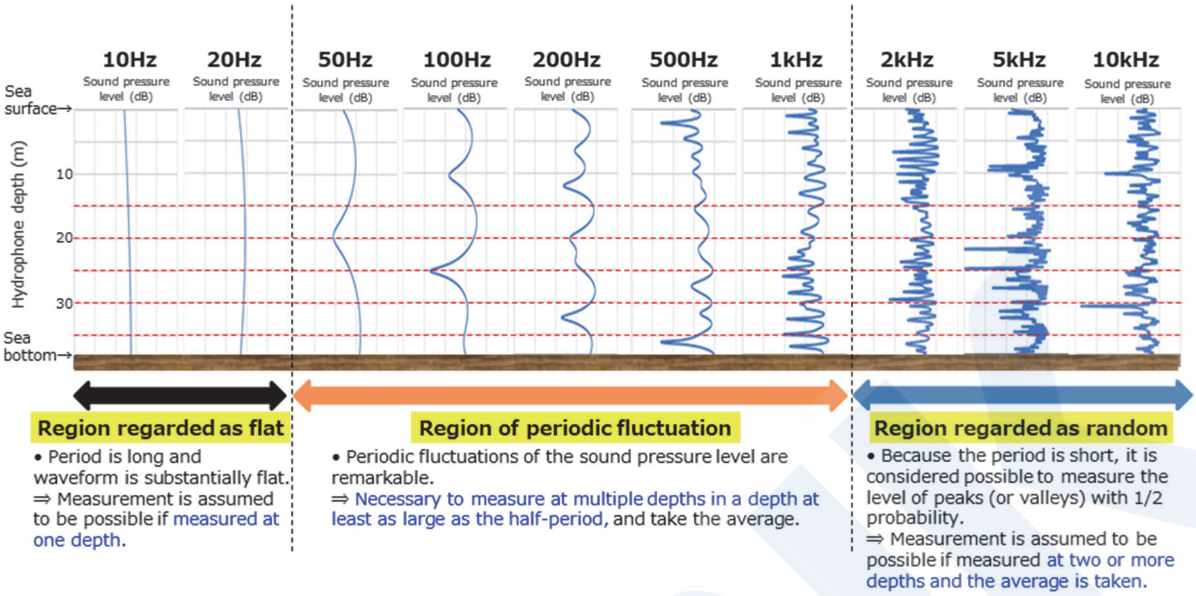


Fig. 10　Additional consideration of situation of sound pressure level fluctuations at each hydrophone setting depth by frequency (water depth of Seto Inland Sea: 38 m)

As can be seen in Fig. 10, at frequencies of 20 Hz and less, the period of the sound pressure level fluctuations due to interference is long, the waveform is substantially flat, and it is assumed the measurement is basically possible even at one depth. In the range from 50 Hz to about 1 kHz, periodic level fluctuations are considered to be remarkable, and it is considered necessary to carry out measurements by depth, using multiple hydrophones in a depth interval equal to or greater than the half-period, and take the average. At 2 kHz and above, the fluctuation period is short, and measurement is assumed to be possible if measurements are made at two or more depths and the average is taken.

To summarize the recommended number of hydrophones and set depths once again:

① The periods of the sound pressure level fluctuations in the depth direction are different, depending on the frequency, and can be divided into three regions.

② As a method for measuring the average level by using multiple hydrophones, the following conditions are deemed appropriate.

- Measurement depth zone: 15 m to 35 m (set so as to cover approximately the half-period in the results for 50 Hz)
- Number of hydrophones: 5 (set so as to cover multiple peaks and valleys in the results for 50 Hz to 500 Hz)

⇒ In the depth range from 15 m to 35 m, measurement at 5 points (15, 20, 25, 30, 35 m) is recommended (shown by the horizontal red dotted lines in Fig. 10)

In actuality, the ship being measured sails at a constant speed and passes across the CPA of the hydrophone array, but since a time measurement of plus/minus a few seconds is acquired while passing through the CPA, the average in the time direction is also added. Although the difference in the route equivalent to the ship's traveling distance during these few seconds is small, it is considered to make an additional significant contribution to the average of the random path difference at frequencies of 2 kHz and above.

4.2.2　Study of Waters Equivalent to Bungo Channel Sea Area (Average Water Depth: 80 m)

Finally, a simulation was attempted with the water depth condition changed to 80 m, which is equivalent to the waters in the vicinity of the Bungo Channel. The setting conditions are shown in Fig. 11, and the situation of interference at each frequency and the recommended depths of the installed hydrophones are shown in Fig. 12.

Other than the water depth setting, the setting conditions are the same as those used above, including the 5 path routes. However, the cutoff frequency was also lowered to around 5 Hz, corresponding to the increased water depth.

As can be understood from Fig. 12, and was also the case with the water depth of 38 m, measurement with one hydrophone is not desirable because multi-path interference causes large fluctuations in the sound pressure level, depending on the hydrophone setting depth. As with the water depth of 38 m, it is advisable to measure the average sound pressure level by receiving the peaks and valleys of fluctuations in the sound pressure level with multiple hydrophones.

In considering the results in Fig. 12, which are similar to the results for the Seto Inland Sea (simulation for water depth of 38 m), the conclusions were essentially unchanged.

① The periods of sound pressure level fluctuations in the depth direction are different, depending on the frequency, and can be divided into three regions. This is the same as in the simulation for the Seto Inland Sea.

② As a method for measuring the average level by using multiple hydrophones, the following conditions are considered appropriate.

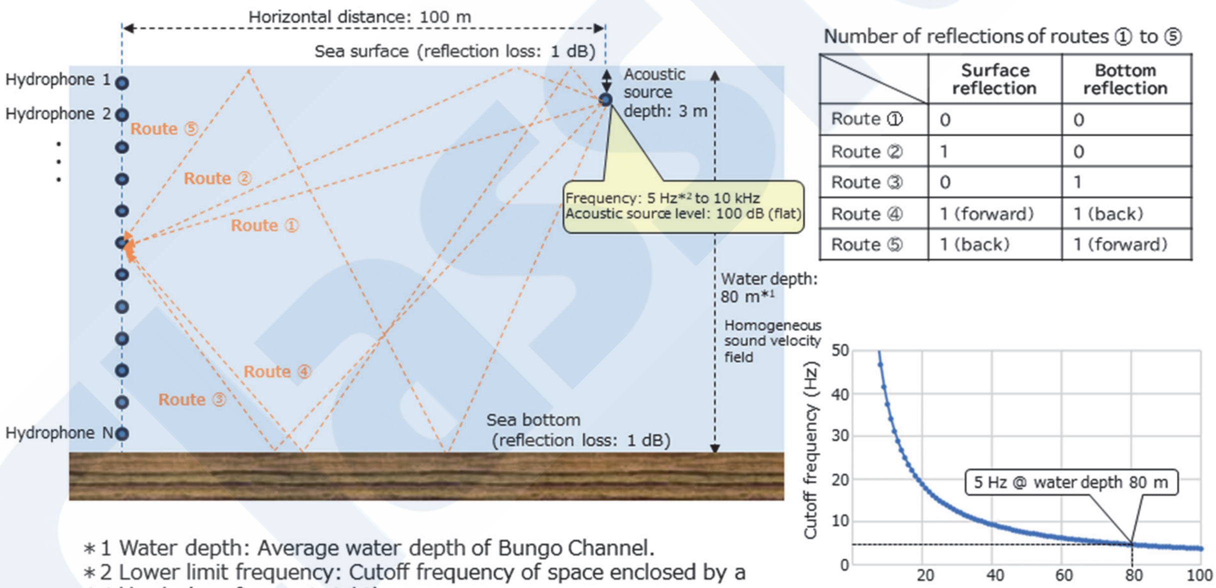
- Measurement depth zone: 30 m to 70 m (set so as to cover approximately the half-period in the results for 20 Hz)
- Number of hydrophones: 5 (set so as to cover multiple peaks and valleys in the results for 10 Hz to 200 Hz)

⇒ In the depth range from 15 m to 35 m, measurement at 5 points (15, 20, 25, 30, 35 m) (shown by the horizontal red dotted lines in Fig. 10)

As one difference from the case of the water depth of 38 m (Seto Inland Sea), the region regarded as random is broader.

Since measurement in the periodic fluctuation region requires 5 hydrophones, if the measurement depth is increased further, approaching the condition of the 2023 Guidelines, it is expected to approach to the average of 3 hydrophones.

As already discussed, if the 2023 Guidelines are followed faithfully, the appropriate measurement locations for securing the necessary water depth will be limited, a large-scale system will be required, and the burden on ship owners will also increase. In the future, the author believes that “the development of more concrete systems that enable measurements as easily as possible, in any location (with almost no restrictions)” will be an issue for continuing study, and would like to conclude this paper with a proposal for proceeding in the future.



	Surface reflection	Bottom reflection
Route ①	0	0
Route ②	1	0
Route ③	0	1
Route ④	1 (forward)	1 (back)
Route ⑤	1 (back)	1 (forward)

＊1 Water depth: Average water depth of Bungo Channel.
＊2 Lower limit frequency: Cutoff frequency of space enclosed by a rigid body (see figure at right).

Fig. 11 Conditions of multi-path simulation (water depth in Bungo Channel area: 80 m)

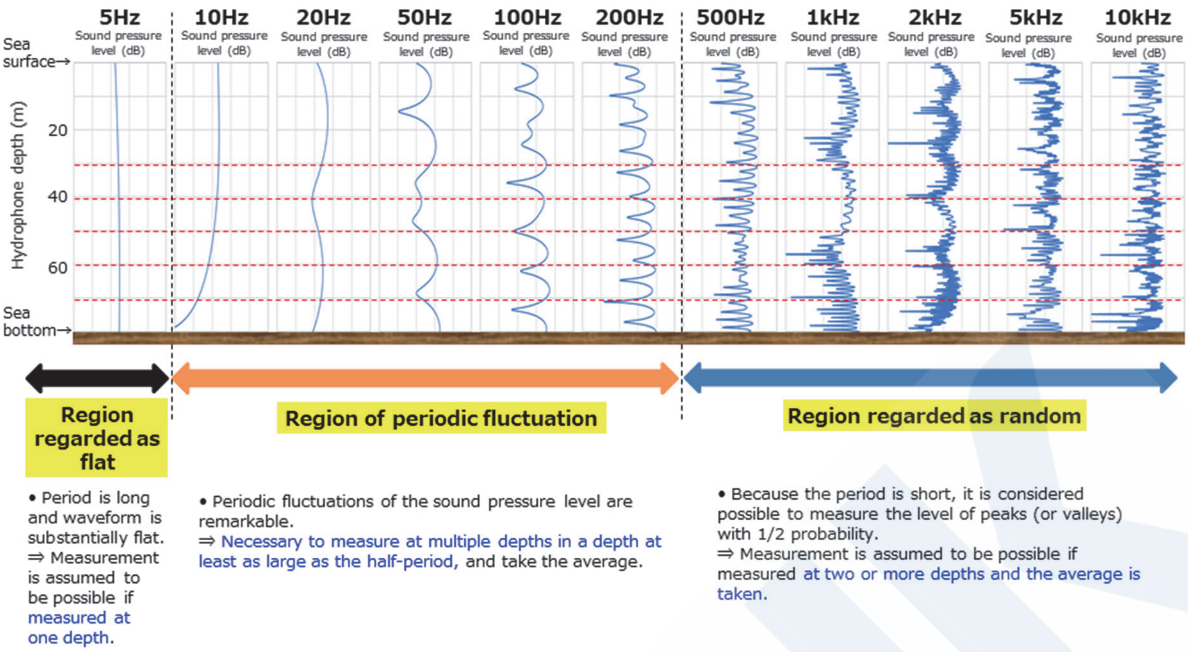


Fig. 12 Additional consideration of situation of sound pressure level change at each hydrophone setting depth by frequency (water depth in Bungo Channel area: 80 m)

5. PROPOSAL FOR PROCEEDING IN THE FUTURE

Considering the regulations on ship noise measurement expected in the future, methods that are suitable for Japan and can also reduce the burden on ship owners should be studied with all stakeholders in the maritime industry.

- ◆ Candidate measurement sites should be proposed, and if necessary, the parameters of simulations should be adjusted to represent a more realistic environment (water temperature, topography, water depth, etc.) corresponding to the conditions, in order to improve the accuracy of simulations.
- ◆ Based on actual data for real sea areas and simulation results, more concrete measurement systems should be constructed and proposed.
- ◆ The proposed systems should be materialized and measurements should be verified in actual seas areas as quickly as possible.