# Development and Application of Ship Underwater Radiated Noise Estimation Tool for Preservation of the Marine Environment

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## 1. INTRODUCTION

The effects of underwater radiated noise (URN) generated by commercial shipping on marine ecosystems have become important issues in the International Maritime Organization (IMO). At the 66th session of the Marine Environment Protection Committee (MEPC 66) held in April 2014, "GUIDELINES FOR THE REDUCTION OF UNDERWATER RADIATED NOISE FROM COMMERCIAL SHIPPING TO ADDRESS ADVERSE IMPACTS ON MARINE LIFE" (MEPC.1/Circ.833) was approved. While these Guidelines are not mandatory, they present directions for the reduction of underwater radiated noise (URN) in each of the stages of ship design, construction, operation and maintenance. Subsequently, a draft revision of the Guidelines was prepared at the 9th session of the Sub-Committee on Ship Design and Construction (SDC 9) in January 2023, and the draft revision was approved as "REVISED GUIDELINES FOR THE REDUCTION OF UNDERWATER RADIATED NOISE FROM SHIPPING TO ADDRESS ADVERSE IMPACTS ON MARINE LIFE" (MEPC.1/Circ.906) at MEPC 80 in July of the same year. The revised guidelines include new provisions related to the development of underwater radiated noise management plans (URN management planning). URN Management Plans consist of the elements of setting standard values and development of reduction targets for URN generated by ships, technical and operational reduction methods, and periodic monitoring and evaluation.

With this situation as background, the National Maritime Research Institute (NMRI) has been carrying out research on a simple estimation method for calculating the URN level of actual ships. Previous research has shown that the velocity effect of propeller cavitation noise of actual ships can be understood by an equation that combines Brown's formula and HOPE Light (a ship performance estimation program developed by the NMRI) [1]. To improve URN estimation accuracy, the cavitation area estimation method has also been enhanced[2]. The cavitation area has been estimated by numerical analysis while varying the main parameters such as the propeller rotational speed and advance coefficient, the cavitation number, etc., and a database has been constructed from the results. Based on this database, a practical cavitation area estimation chart (DB chart) has been prepared. The cavitation area was estimated using the DB chart, and the accuracy of the simplified estimation method has been improved by calculating the URN level using those values and Brown's formula.

This paper introduces the simplified estimation method for URN developed by the NMRI. Furthermore, it presents a comparison between the actual measurement results of URN emitted by a bulk carrier off the southern coast of Oshima Island and the estimated results obtained using the simplified estimation method, to evaluate the effectiveness of the proposed approach.

## 2. SIMPLIFIED ESTIMATION METHOD FOR UNDERWATER RADIATED NOISE

The proposed method calculates URN levels using Brown's formula, which is a simplified estimation formula for URN. The parameters required for Brown's formula are estimated using "HOPE Light," a hull form optimization program developed by NMRI [4]. AIS data from target ships are used as input data for HOPE Light. In the conventional method, the cavitation area had been estimated using the Burrill cavitation diagram [5], but because the Burrill diagram is primarily intended for high-speed vessels, the cavitation area tended to be underestimated when this method is applied to general merchant ships. Therefore, in the simplified estimation method, a "DB chart," which is a cavitation area estimation chart for general merchant ships, was newly constructed with the aim of improving the accuracy of estimations of the cavitation area by using this chart, and as a result, also improving the accuracy of the URN estimation method. The following sections explain the specific URN level estimation method.

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## 2.1 Brown's Formula

The proposed method estimates ship URN using Brown's formula [3]. Brown's formula, shown in Eq. (1), is an empirical formula derived from actual ship URN measurement results. The use of Brown's formula makes it possible to estimate the upper limit of the underwater sound pressure level ($SPL$) over a wide frequency range of approximately 100 Hz to 10 kHz based on the propeller rotational speed, propeller diameter, number of propeller blades (blade count), and the cavitation area.

$$SPL = 10\log\left(\frac{n^3 D_p^4 Z}{f^2}\right) + 10\log\left(\frac{A_c}{A_D}\right) + K \tag{1}$$

Where, $SPL$: underwater sound pressure level [dB], $f$: frequency [Hz], $K$: constant (propeller: $K$=163, thruster: $K$=170), $n$: propeller rotational speed [rps], $D_p$: propeller diameter [m], $Z$: number of propeller blades [ – ], $A_C/A_D$: cavitation area ratio [ – ], $A_C$: cavitation area [$\mathrm{m}^2$] and $A_D$: propeller disc area [$\mathrm{m}^2$].

In the proposed method, the parameter $n$ and $D_p$ necessary in Brown's formula are estimated using HOPE Light. An outline of HOPE Light is presented in the following section 2.2. The number of propeller blades was set to 4, and the cavitation area ratio $A_C/A_D$ is estimated from the DB chart prepared using numerical calculations. An outline of the DB chart is presented in section 2.3.

## 2.2 HOPE Light

The parameters necessary for estimation of the URN level of a target ship were estimated by using "HOPE Light," a program for optimization of the hull form dimensions of ships developed by NMRI [4]. This program can obtain not only the propulsion performance of the target ship, but also the maneuverability, course stability and other operational performance characteristics of the ship. As one distinctive feature, it can also estimate the fuel consumption of the main engine, auxiliary engines, etc., suited to the target ship.

As the basic input for HOPE Light, the ship type and principal particulars are necessary. These input data can be obtained from the AIS data and the principal particulars database. The parameters necessary for Brown's formula, which is a simple estimation formula for URN level, are extracted from the calculation results obtained from HOPE Light. In the simplified estimation method, Excel sheets were prepared for the URN level estimations, and the URN levels were calculated through integration of these sheets and HOPE Light.

## 2.3 DB Chart

In the proposed URN estimation method, DB charts were newly developed for typical merchant ships. First, the propeller to be used as a standard is selected, and propeller groups are formed by revising its pitch and expanded blade area. The cavitation area for these propeller groups is calculated for various propeller loads and cavitation numbers, and DB charts are then constructed by arranging the cavitation area data obtained from the numerical calculations.

The cavitation area is estimated using the lift equivalent method [6]. The method used in calculations of the pressure distribution on the propeller blade surface during wake flow, which is necessary for application of the lift equivalent method, is the unsteady marine propeller performance calculation method [7, 8] based on the simplified surface panel method (SQCM: Source and Quasi-Continuous Method), which was developed by Kyushu University.

The MAU propeller is used as the prototype propeller for creation of the DB charts [9]. The number of propeller blades was set to 4. Twenty propeller groups were created by varying the propeller pitch ratio and the expanded blade area ratio. Three kinds of wake distributions were used: the JBC (Japan Bulk Carrier) [10], KCS (KRISO Container Ship) [11] and the KVLCC2 (KRISO Very Large Crude Carrier) [11] (KRISO: Korea Research Institute of Ships and Ocean Engineering). The wake distributions of these three ship types are shown in Figs. 1-3. The details of the DB charts are shown in Table 1. The cavitation area estimation charts were prepared by estimating the largest cavitation areas of the 20 propeller groups for these three types of wake distributions by varying the propeller loading and the cavitation number, and arranging the results. In this paper, for example, when the target propeller (MAU) has an expanded blade area ratio $a_E$= 0.6 and a pitch ratio $H/D_P$ = 0.6, the propeller is denoted as MAU0606, and when the wake distribution is the JBC and the target propeller is MAU0606, the DB chart is denoted as JBC-MAU0606.

Table 1　Detail of cavitation area estimation charts

| Item | Num. of items | Parameter |
|---|---|---|
| Propeller Blade | 1 | MAU |
| Expanded Blade Area Ratio ($a_E$) | 4 | 0.4, 0.5, 0.6, 0.7 |
| Pitch Ratio ($H/D_P$) | 5 | 0.6, 0.7, 0.8, 0.9, 1.0 |
| Wake Distribution | 3 | JBC, KCS, KVLCC2 |
| Number of Charts | 60 | - |

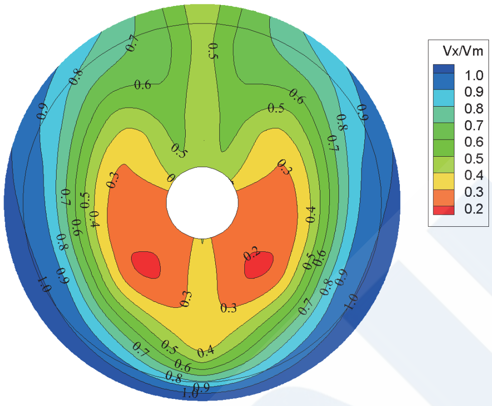


Fig. 1　Wake distribution of JBC

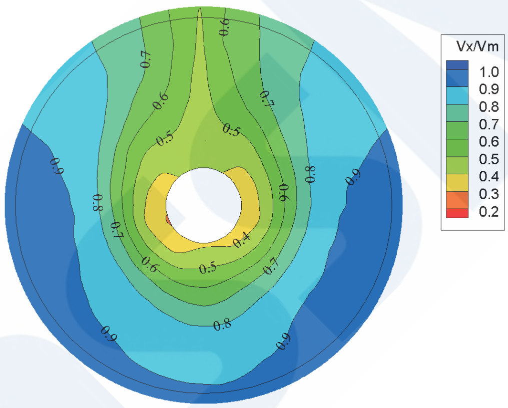


Fig. 2　Wake distribution of KCS

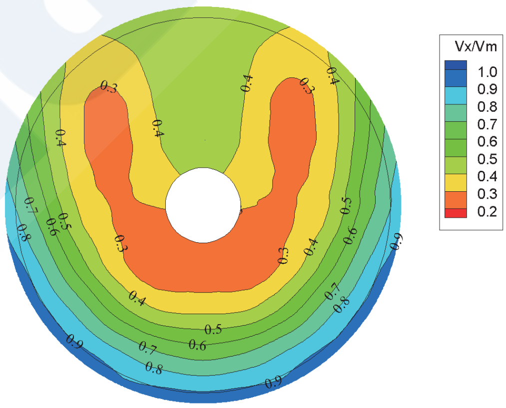


Fig. 3　Wake distribution of KVLCC2

As examples of the DB charts prepared in the simplified estimation method, the results of estimations of the cavitation areas of the following six types of propellers with the JBC wake distribution are shown in Figs. 4-9.

・Expanded blade area ratio series: JBC-MAU0506, JBC-MAU0606, JBC-MAU0706

・Pitch ratio series: JBC-MAU0607, JBC-MAU0608, JBC-MAU0609

Fig. 4 to Fig. 9 show the cavitation coefficient (cavitation number) $\sigma_{0.7R}$ on the $x$-axis and the propeller load $\tau_c$ on the $y$-

axis, and give the upper limit at which cavitation will not occur. $\sigma_{0.7R}$ and $\tau_c$ are expressed by Eq. (2) and Eq. (3), respectively. The circumferential velocity $V_R$ at the 0.7 $R$ position on the propeller radius is expressed by Eq. (4).

$$\sigma_{0.7R} = \frac{p - e}{1/2\rho V_R^2} \tag{2}$$

$$\tau_C = \frac{T}{1/2\rho A_P V_R^2} \tag{3}$$

$$V_R = \sqrt{V_A^2 + (0.7D_P\pi n)^2} \tag{4}$$

Where, $\tau_c$: propeller load [ – ], $T$: thrust [N], $\rho$: density of fluid [kg/m$^3$], $A_p$: projected area of propeller [m$^2$], $V_A$: propeller inflow velocity [m/s], $V_R$: circumferential velocity at propeller radius 0.7 $R$ position [m/s], $\sigma_{0.7R}$: cavitation number (at 0.7 $R$ position) [ – ], $p$: water pressure at propeller radius 0.7 $R$ position [Pa], $e$: pressure of water vapor [Pa] and $D_p$: propeller diameter [m].

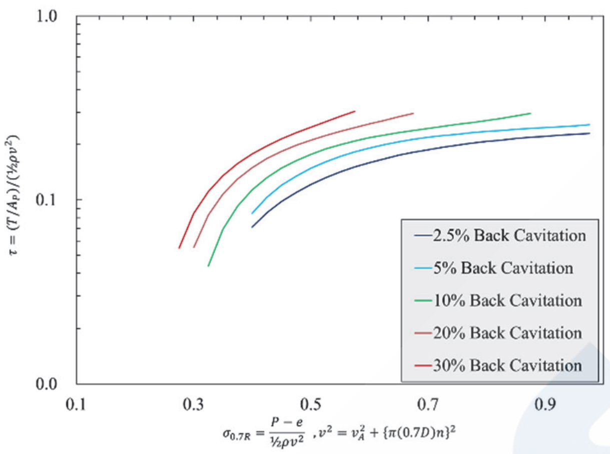


Fig. 4 Cavitation area estimation chart: JBC-MAU0506

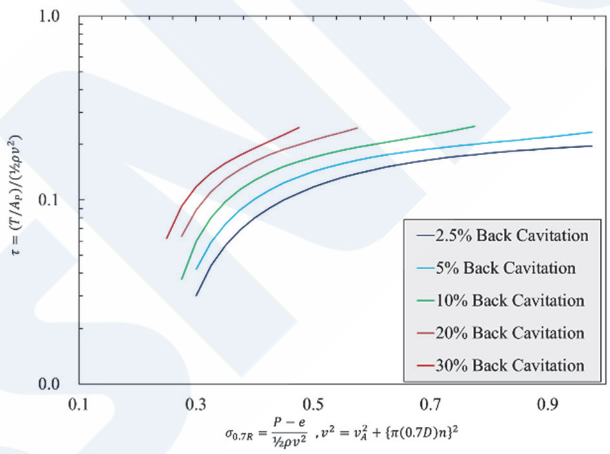


Fig. 5 Cavitation area estimation chart: JBC-MAU0606

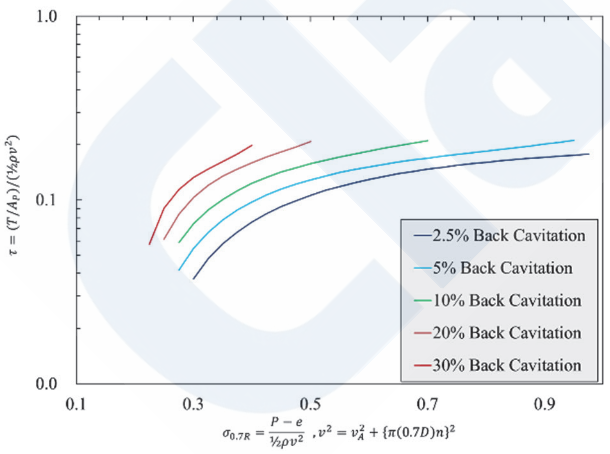


Fig. 6 Cavitation area estimation chart: JBC-MAU0706

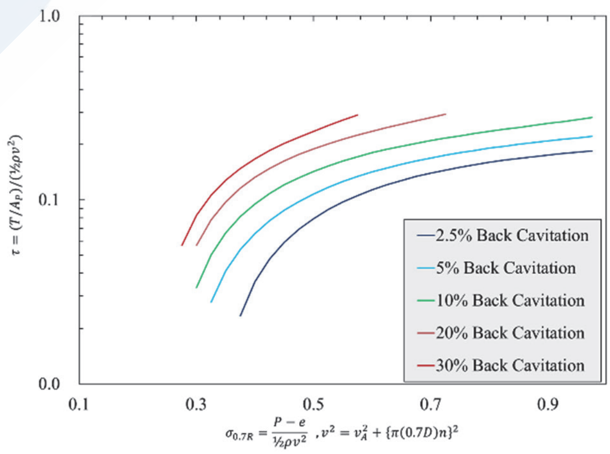


Fig. 7 Cavitation area estimation chart: JBC-MAU0607

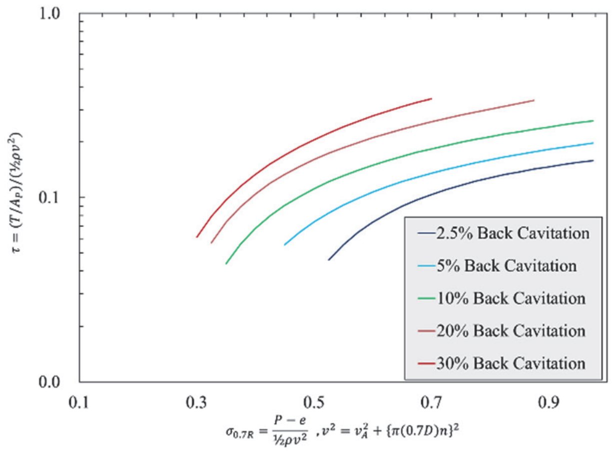


Fig. 8 Cavitation area estimation chart: JBC-MAU0608

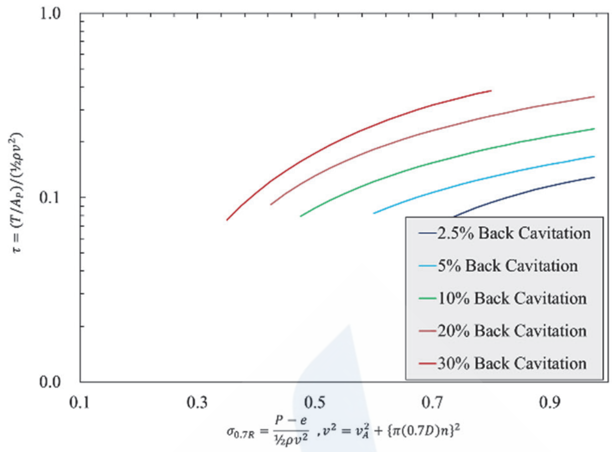


Fig. 9 Cavitation area estimation chart: JBC - MAU0609

## 2.4 Method of Implementation in URN Estimation Method

The DB charts described in section 2.3 were incorporated into HOPE Light, and a function for estimating the cavitation area from the DB charts was added. Specifically, in this system, the pitch ratio and expanded blade area ratio of the propeller of the target ship, which are output from HOPE Light, and the DB chart corresponding to the wake distribution of the target ship are searched. Then, based on the searched chart, the cavitation area corresponding to the propeller load and the cavitation number of the target ship output from HOPE Light is calculated. Finally, the URN level of the target ship is estimated by substituting that result (cavitation area) into Brown's formula.

# 3. VERIFICATION BY ACTUAL SHIP MEASUREMENT DATA

A comparative study with the URN data obtained by measurement of actual ships was conducted to verify the accuracy of the improved URN estimation method. The verification work related to the accuracy of the improved method was carried out by comparing the values of underwater radiated noise in the waters off the southern coast of Oshima Island, which were collected in the Underwater Noise Countermeasures Study Project in the past, and the calculated results obtained by this URN estimation method.

## 3.1 Outline of Actual Ship Measurements Off Southern Coast of Oshima Island

In the Underwater Noise Countermeasures Study Project, hydrophones were installed in the waters off the southern coast of Oshima Island, and URN data from ships sailing in the vicinity were collected. Using these actual ship measurement data, a comparative study between the URN estimation method adopted in the present research and the actual ship measurement data was conducted. The details of the actual ship measurement data are described in the paper by Sakai *et al.* [12]. The objective of the present analysis was actual ship measurement data for large ships with a length between perpendiculars $L_{pp}$ of 100 m and longer. From the measurement data for these large ships, data where tidal current effects were limited and cruising speeds closely matched design speeds were selected. The following filtering conditions were applied:

・Data with a difference ≥1 kt between AIS speed over ground and speed through water were excluded due to significant tidal current effects.

・Data in which the ship's speed at the time of measurement was <30 % of its design speed were excluded as abnormal values.

Five bulk carriers were extracted from the selected actual ship measurement data, and the level of URN was estimated for each ship and compared with the actual ship measurement results. The principal particulars of the extracted target ships are shown in Table 2.

## 3.2 Comparison of Actual Ship Measurement Results and Estimation Results

Using the conventional and improved URN estimation methods, the URN levels of the actual ships were estimated for the target ships described in section 3.1, and the estimation results and actual ship measurement results were compared. Fig. 10 to Fig. 14 show the actual ship measurement results of the bulk carriers and the URN estimation results obtained by the conventional estimation method and improved estimation method. In these figures, the blue marker line shows the actual ship measurement results, the dark blue broken line shows the estimation results of the conventional method, and the red solid line shows the estimation results obtained by the improved method. From Fig. 10 to Fig. 14, compared with the conventional method, the estimated values of the URN level obtained with the improved method increased and approached the actual ship measurement values.

Table 2 Principal particulars and ship speeds of bulk carriers used for verification

| No. | $L_{pp}$ [m] | $B$[m] | $D$[m] | $Vs$[kt] |
|---|---|---|---|---|
| 203 | 195 | 32 | 13 | 10 |
| 208 | 225 | 32 | 15 | 14 |
| 231 | 178 | 32 | 12 | 14 |
| 246 | 229 | 43 | 14 | 12 |
| 282 | 288 | 45 | 18 | 13 |

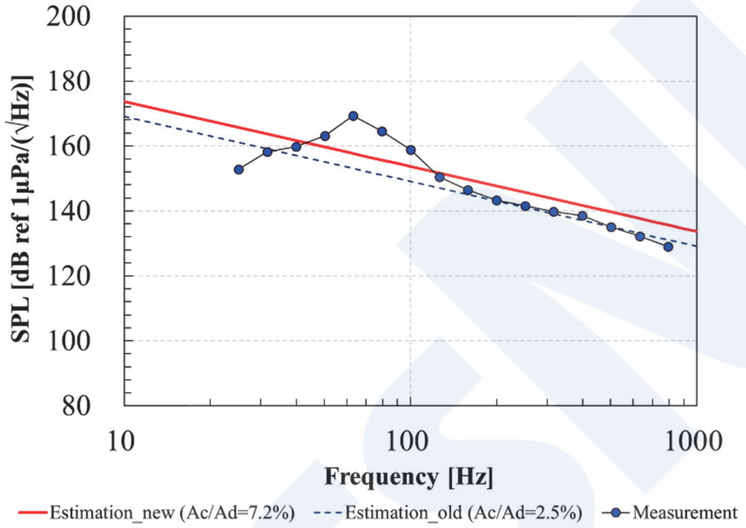


Fig. 10 The results of No.203 bulk carrier ($L_{pp}$=195m, $Vs$=10kt)

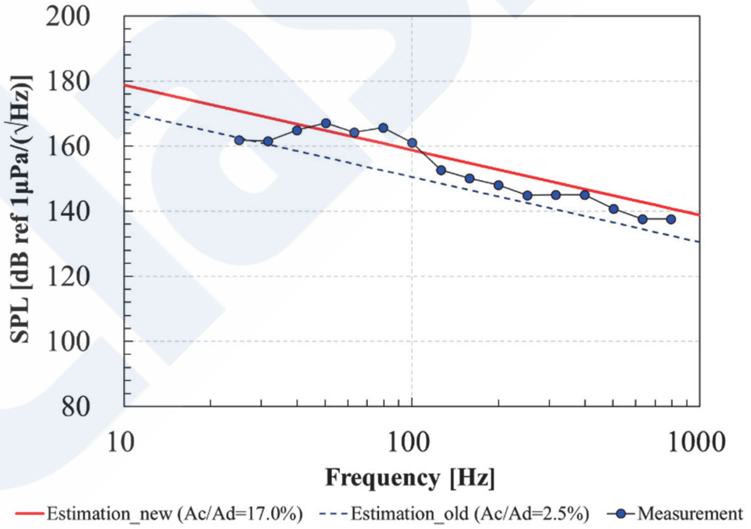


Fig. 11 The results of No.208 bulk carrier ($L_{pp}$=225m, $Vs$=14kt)

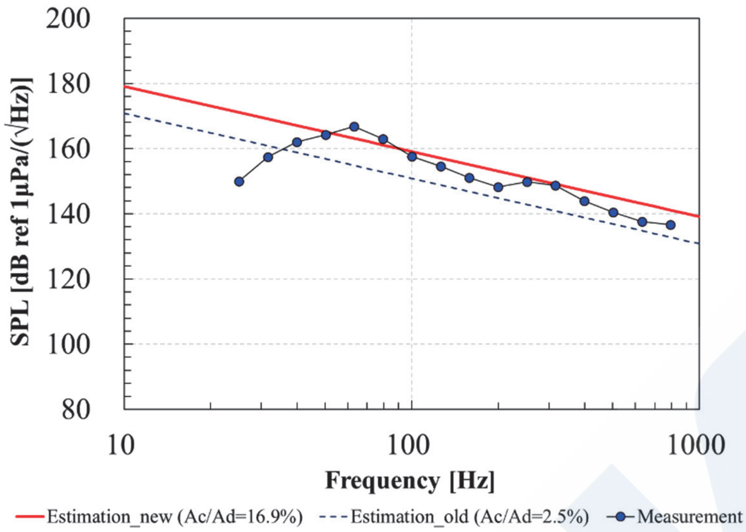


Fig. 12 The results of No.231 bulk carrier ($L_{pp}$=178m, $Vs$=14kt)

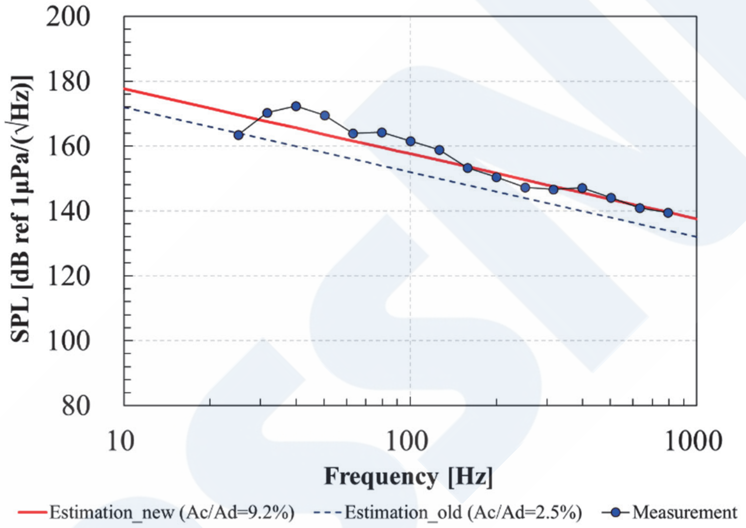


Fig. 13 The results of No.246 bulk carrier ($L_{pp}$=229m, $Vs$=12kt)

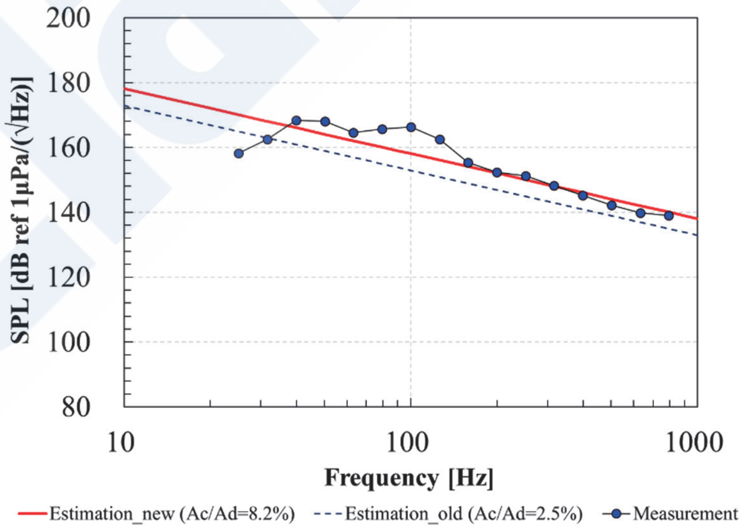


Fig. 14 The results of No.282 bulk carrier ($L_{pp}$=288m, $Vs$=13kt)

## 3.3 Discussion

To quantitatively evaluate the actual ship measurement results and estimated values by the URN estimation methods presented in section 3.2, the error between the two sets of results was evaluated. The RMSE (Root Mean Square Error) of the measurement results and the estimated values at the center frequencies of each 1/3 octave band was calculated, and the estimation accuracy was verified by comparing the RMSE of the conventional method and the improved method. The center frequencies in this evaluation are 25, 32, 40, 50, 63, 79, 100, 126, 158, 200, 251, 316, 398, 501, 631 and 794 [Hz]. Table 3 and Fig. 15 show the RMSE evaluation results for the bulk carriers. Compared with the RMSE of 7.0 [dB] of the conventional method, the RMSE of the improved method was 5.2 [dB], representing an accuracy improvement of approximately 1.8 [dB] (approximately 26 %). This result shows that the accuracy of the URN estimation method can be improved significantly by adopting the cavitation area estimation charts that consider the propeller geometry and wake distribution. As the main factor for the increased accuracy of the improved method, more accurate estimation of the cavitation area reflecting the propeller geometry is now possible by using cavitation area estimation charts that consider the propeller pitch ratio and expanded blade area ratio, as well as the wake distribution, resulting in enhanced accuracy in estimation of the cavitation area.

Table 3 Results of RMSE assessments of bulk carriers

| No | $L_{pp}$ [m] | *Vs*[kt] | *RMSE_old*[dB] | *RMSE_new*[dB] |
|---|---|---|---|---|
| 203 | 195 | 10.2 | 6.6 | 6.2 |
| 208 | 225 | 13.5 | 6.6 | 4.6 |
| 231 | 178 | 14.0 | 6.9 | 6.9 |
| 246 | 229 | 11.7 | 7.6 | 3.4 |
| 282 | 288 | 13.1 | 7.4 | 4.7 |
| | | Average | 7.0 | 5.2 |

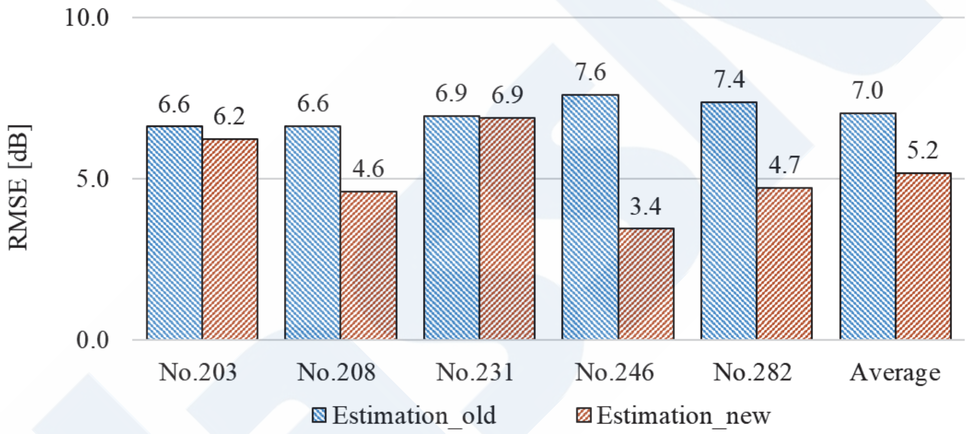


Fig. 15 Comparison of RMSEs for bulk carriers

## 4. CONCLUSION

This paper has introduced the simplified estimation method for estimating URN levels of merchant vessels using design-stage information. The method constructs database (DB) charts for estimating cavitation areas of typical merchant ships and improves URN estimation accuracy by combining these charts with Brown's formula.

The key features and achievements of the proposed method are:

· Enhanced cavitation area estimation accuracy compared to conventional Burrill chart methods through the development of DB charts based on numerical calculations for merchant vessels.

· High-accuracy cavitation area estimation considering propeller geometry and stern wake distribution through the use of DB charts that account for propeller pitch ratio, expanded blade area ratio, and wake distribution.

· Validation through comparison with actual vessel measurement data obtained in waters off southern Oshima Island, demonstrating improved estimation accuracy for all five examined bulk carriers compared to the conventional method.

· Quantitative accuracy improvement shown by RMSE evaluation at 1/3 octave band center frequencies, where the average RMSE decreased from 7.0 dB (conventional method) to 5.2 dB (proposed method), representing approximately 26% improvement in estimation accuracy.

The proposed method is expected to serve as an effective tool for evaluating URN during ship design phases and developing

URN management plans in compliance with IMO guidelines.

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