# Research and Development of OCTARVIA Project

## -Evaluation of Ship Performance in Actual Seas-

by

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Abstract

Recent studies have highlighted the importance of evaluating whether a ship's propulsive performance is as designed in both calm seas and actual seas. Various monitoring instruments and systems have been developed and fitted onboard to check the performance of ships in service. Research and development for analyzing onboard monitoring data, predicting ship performance in actual seas and its evaluation have been carried out as part of the OCTARVIA project. The results of the project are summarized in the recommended guidelines and calculation programs. This paper presents the background of the establishment of the project, followed by the contents of the guidelines and programs.

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## Nomenclature

Subscription $M$ shows the value of the model
$A_L$ : the projected lateral area above sea surface
$A_T$ : the projected transverse area above sea surface
$B$ : the ship breadth
$B_0$ : the coefficient representing interference by the hull and the propeller
$C_0$ : the coefficient representing propeller interference against wake
$C_G$ : the resistance increase coefficient due to interference by the hull and propeller
$C_T$ : the propeller load
$C_{T,SW}$ : the propeller load at the ship self-propulsion point in still water
$C_X$, $C_Y$, $C_N$ : the non-dimensional coefficients of longitudinal force, lateral force and yaw moment due to wind, respectively
$D_P$ : the propeller diameter
$d$ : the ship draught
$d_{aft}$ : the ship draught at A.P.
$F_D$ : the towing force
$Fr$ : Froude number
$G$ : the resistance increase due to interference by the hull and propeller
$g$ : the gravitational acceleration
$H$ : the significant wave height

$H_{BR}$ : the navigation bridge height from the sea surface
$J$ : the propeller advance ratio
$K_{AW}$ : the non-dimensional coefficient of added resistance in regular waves
$K_T$ : the thrust coefficient
$K_Q$ : the torque coefficient
$K_{XX}$, $K_{YY}$, $K_{ZZ}$ : the lateral radius of gyration, the longitudinal radius of gyration and the yaw radius of gyration, respectively
$L_{OA}$ : the length overall
$L_{PP}$ : the length between perpendiculars
$L_{wl}$ : the waterline length
$N_{wind}$ : the yaw moment due to wind
$n$ : the rate of propeller revolution
$Q$ : the propeller torque
$R_0$ : the resistance without a propeller in still water
$R_{AW}$ : the added resistance in regular waves
$R_{Cw}$ : the ship resistance when the thrust becomes 0
$R_T$ : the total resistance of the ship
$SFC$ : the skin frictional correction
$T$ : the propeller thrust
$T_{01}$ : the mean wave period
$T_\phi$ : the rolling period
$U$ : the wind speed
$U_{a0}$ : the effective wake coefficient at thrust 0 in still water
$U_{a0wc}$ : the effective wake coefficient at thrust 0
$\Delta U_{a0wc}$ : the change of the wake coefficient by the influence of incident waves and ship motion
$U_w$ : the representative wind speed
$V$ : the speed through water
$V_{AM}$ : the propeller advance speed of the model
$V_w$ : the mean wind speed
$X_{wind}$ : the longitudinal force due to wind
$Y_{wind}$ : the lateral force due to wind
(1-$t$) : the thrust deduction coefficient
$(1-t)_{SW}$ : the thrust deduction coefficient at the ship self-propulsion point in still water
(1-$w$) : the wake coefficient
$(1-w)_{SW}$ : the wake coefficient at the ship self-propulsion point in still water
$\Delta(C_T)$ : the difference of $C_T$ between the ship self-propulsion point in the weather condition for evaluation and that in still water
$\Delta(\sqrt{C_T})$ : the difference of $\sqrt{C_T}$ between the ship self-propulsion point in the weather condition for evaluation and the ship self-propulsion point in still water.
$\Delta_{des}$ : the ship displacement at design condition
$\Delta_{ope}$ : the ship displacement at operation condition
$\Delta U_{a0wc}$: the change of the wake coefficient by the influence of incident waves and ship motion
$\rho$ : the fluid density
$\lambda$ : the wave length
$\zeta_a$ : the wave amplitude of incident waves

$\eta_B$ : the propeller efficiency behind the ship
$\eta_o$ : the propeller efficiency in open water
$\eta_R$ : the relative rotative efficiency
$\eta_{R,SW}$ : the relative rotative efficiency at the ship self-propulsion point in still water

## 1. Introduction

Prevention of global warming is highly required internationally, and efforts are being made in each sector. Accordingly, the reduction of greenhouse gas (GHG) emission from international shipping will be further strengthened by regulations. In order to construct, operate, and maintain ships with low GHG emissions in actual operations, technology development is required.

Monitoring, Reporting and Verification by EU (EU-MRV)[1] and Data Collection System by IMO (DCS)[2] start to report fuel consumption for ships. The data of EU-MRV reveals facts of more than 12,000 ships. However, the data is an annual collection of figures including the effects of weather conditions, aging deterioration and so on. It remains questionable whether individual vessels can be evaluated based on these figures. Further, EU will start market based measures from 2023 including shipping sector in emission trading system, to accelerate the GHG reductions[3].

In order to reduce GHG emissions from ship operation, it is necessary to accurately estimate ship performance in actual seas. The EU project "SHOPERA" was conducted to evaluate whether a ship maintains sufficient power to ensure course-keeping performance in adverse weather conditions[4]. Various series of tank tests were carried out and the prediction model was developed. In succession, the EU project "HOLISHIP" was carried out with the aim of integrating these developed technologies, utilizing them in hull form design, and improving the life cycle performance of ships[5].

In Japan, a joint research project started to develop a "scale", performance index, which accurately evaluates ship performance such as speed and fuel consumption in a sea area where waves and winds are actually acting on ships.

In this paper, background of the establishment of the project "OCTARVIA project" is introduced, thereafter the contents of the research and development of the project is explained. Then the contents of the established seven recommended guidelines, developed three calculation programs and the life cycle fuel consumption as a "scale" of the evaluation of ship performance in actual seas are explained.

## 2. OCTARVIA Project

### 2.1 Japan Maritime Cluster Collaborative Research

Based on changes in the business environment surrounding the maritime industry, such as changes in Japan's economic and industrial structure and international trends in safety and environmental regulations, volunteer members from the maritime industry examined how to build internationally fair competitive field. As a result, it was concluded that integration of human resources and technologies of industry, academia and government, which are indispensable for the sustainable development of Japan's maritime industry is to be progressed and common and long-term research themes and maximize the results by maritime clusters based on a strategic approach are to be conducted[6]. Basic principles and classification of research themes for Japan Maritime Cluster Collaborative Research are shown in Fig. 1.

### 2.2 Project Structure

Project for Evaluation of Ship Performance in Actual Seas -Japan Maritime Cluster Collaborative Research- (OCTARVIA project) has been carried out. The project period is three years from October 2017 to March 2021. The total budget is 660 million yen.

The purpose of OCTARVIA project is as follows; 1) development of a reliable estimation method for ship performance in actual seas and 2) establishment of a "scale", performance index, which can objectively evaluate and compare the ship performance in the world with almost the same accuracy. Life cycle fuel consumption is selected as the scale and the target accuracy for the estimation method is selected as errors within 2% of the main engine fuel consumption in actual seas. The target accuracy is aimed for the world's highest accuracy.

Participants of the project are 25 companies from 8 (octo) sectors shown in Table 1.

*Basic principles*

Conduct common and long-term research themes in which the gathering of maritime clusters is indispensable for the sustainable development of industry.

*Classification of research themes*

(1) Research themes that cannot be carried out or maximize results by a company alone

- research on safety / environment regulations, infrastructure development such as IoT, etc.

(2) Research themes with high risk when carried out by a company alone

Fig. 1 Basic principles and classification of research themes for Japan Maritime Cluster Collaborative Research.

Table 1 Participants of OCTARVIA project at the end of March, 2021.

| Sector | Company Name |
|---|---|
| Shipping company (3) | Kawasaki Kisen Kaisha, Ltd.<br>Mitsui O.S.K. Lines, Ltd.<br>NYK Line |
| Shipbuilding company (12) | Imabari Shipbuilding Co., Ltd.<br>Japan Marine United Corporation<br>Kawasaki Heavy Industries, Ltd.<br>Mitsubishi Shipbuilding Co., Ltd.<br>Mitsui E&S Shipbuilding Co., Ltd.<br>Naikai Zosen Corporation<br>Namura Shipbuilding Co., Ltd.<br>Oshima Shipbuilding Co., Ltd.<br>Shin Kurushima Dockyard Co., Ltd.<br>Shin Kurushima Sanoyas Shipbuilding Co., Ltd.<br>Sumitomo Heavy Industries Marine & Engineering Co., Ltd.<br>Tsuneishi Shipbuilding Co., Ltd. |
| Paint maker (3) | Chugoku Marine Paints, Ltd.<br>Kansai Paint Marine Co., Ltd.<br>Nippon Paint Marine Coatings Co., Ltd. |
| Propeller & rudder maker (3) | Japan Hamworthy Co., Ltd.<br>Kamome Propeller Co., Ltd.<br>Nakashima Propeller Co., Ltd. |
| Governor maker (1) | Nabtesco Corporation |
| Weather consulting company (1) | Japan Weather Association |
| Research institute (1) | National Institute of Maritime, Port and Aviation Technology |
| Classification society (1) | Nippon Kaiji Kyokai |

The project consists of Project Management Conference, Steering Committee, Research Execution Body, Working Group, Research Team and Secretariat. The structures and members are shown in Fig. 2. Each role is as follows; 1) Project Management Conference receives report of research and budget, reviews them and decides matters specified by research participants, 2) Steering Committee considers the above upon receiving a referral, 3) Research Execution Body manages research according to the contract plan and makes coordination between Working Groups, 4) Working Group conducts research under Research Execution Body, 5) Research Team analyzes monitoring data for individual ships etc.

Three Working Groups (WG) are organized according to three sub-themes (S) as follows;

(S1) Establishment of ship performance monitoring method in actual seas

(S2) Establishment of estimation method of ship performance in actual seas

(S3) Establishment of evaluation of ship performance in actual seas.

Eleven Research Teams are established under S1-WG in consideration of the confidentiality of individual ships. The teams are shown in Table 2. Object ships are many types of ship and cover large to small ships. Detailed studies and validations were carried out on these ships.

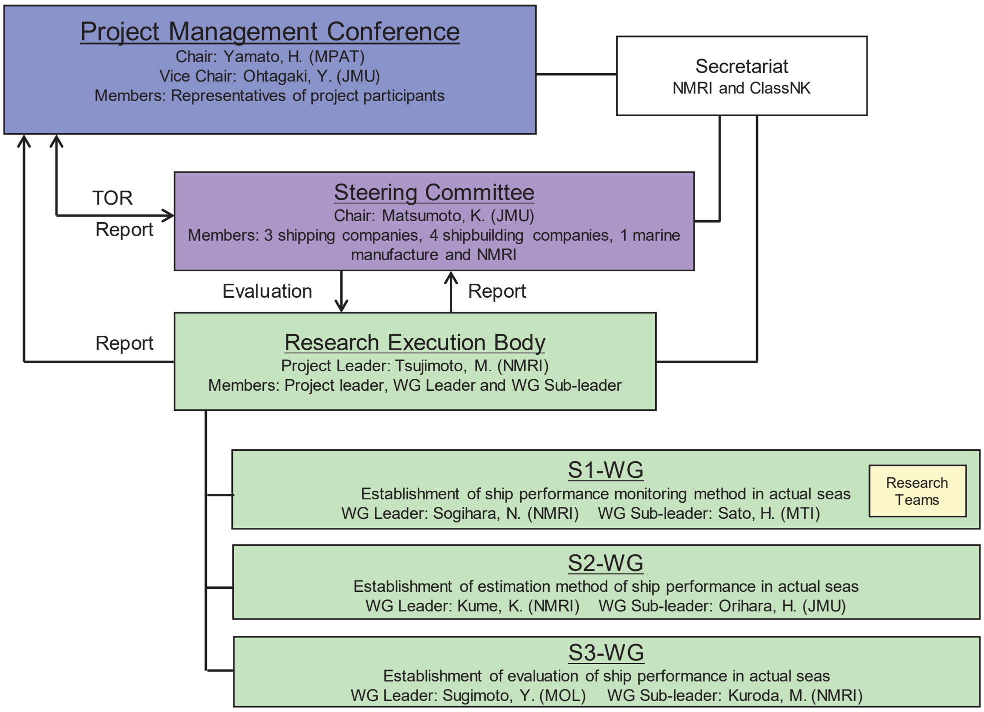



Fig. 2 Project structure.

Table 2 Research teams and object ships.

| Research team | Ship type |
|---|---|
| #1 | Container ship (Panamax) |
| #2 | Container ship-A (over-Panamax) |
| #3 | Container ship-B (over-Panamax) |
| #4 | Ocean going PCC-A |
| #5 | Ocean going PCC-B |
| #6 | Mini-Cape size bulk carrier-A |
| #7 | Mini-Cape size bulk carrier-B |
| #8 | Very Large Ore Carrier (VLOC) |
| #9 | Tanker (MR) |
| #10 | Tanker (VLCC) |
| #11 | Training ship |

## 3. Establishment of recommended guidelines

OCTARVIA project established following 7 kinds of guidelines which required for analysis, prediction and evaluation of ship performance in actual seas. The contents are described here.

1) Recommended Guidelines for Onboard Monitoring
2) Recommended Guidelines for CFD Calculations to Estimate Wind Forces in Actual Seas
3) Recommended Guidelines for CFD Calculations to Estimate Resistance Increases due to Head Waves
4) Recommended Guidelines for Wind Tunnel Test to Estimate Ship Performance in Actual Seas
5) Recommended Guidelines for Tank Tests in Waves to Ship Performance in Actual Seas
6) Recommended Guidelines for Tank Test Analysis in Waves to Ship Performance in Actual Seas
7) Recommended Guidelines for Estimating Ship Performance in Actual Seas

### 3.1 Recommended Guidelines for Onboard Monitoring

Target accuracy is set to estimate fuel consumption in actual seas within 2% errors. Based on it, required measurement items and the instruments with allowable errors for the performance estimation is summarized in the guidelines as shown in Table 3. In addition to the table, it is preferable to use the following variables for detailed measurements.

Fuel consumption
Fuel properties (specific gravity, calorific volume)
Sea water temperature
Temperature, atmospheric pressure
Water depth
Ship motion
Wave spectrum

Table 3 Measurement items and instruments with allowable errors.

| Measurement item | Measuring instruments, data acquisition method | Allowable errors (Catalog value) |
|---|---|---|
| Speed over ground | GNSS | 2% |
| Speed through water | Speed log | 1% |
| Shaft horsepower | Shaft horsepower meter | 0.5% |
| Main engine revolution speed | Revolution counter | 1% |
| Heading direction | Gyro compass | |
| Course | GNSS | |
| Wind | Anemometer | Relative wind speed: 5%<br>Relative wind direction: 5 degrees |
| Sea condition | Wave data (hindcast or nowcast data is available), onboard observation (radar, visual observation, etc.) | Wave height: 0.1 m<br>Wave direction: 5 degrees |
| Rudder angle | Rudder angle indicator | |
| Draft | Visual observation at departure | |
| Longitudinal radius of gyration | Measured value or value by recommended estimation method | |

Table 4 Criteria for stability and steadiness of data acquisition

| Purpose | Item | Statistical value | Criteria | Importance |
|---|---|---|---|---|
| Elimination of the effects of acceleration / deceleration | rate of main engine revolution | Mean | 40% or less of rate of main engine revolution at MCR | Mandatory |
| | | Standard deviation | 3rpm or less | Optional |
| | Speed over ground | Standard deviation | 0.5 knot or less | Optional |
| | Speed through water | Standard deviation | 0.5 knot or less | Optional |
| | Shaft horsepower | Standard deviation | 5% of MCR or less | Optional |
| Elimination of the steering effect | Rudder angle | Mean | 5 degrees or less (absolute value) | Mandatory |
| | | Standard deviation | 1 degree or less | Optional |
| | Drift angle | Mean | 3 degrees or less (absolute value) | Mandatory |
| | Heading direction | Standard deviation | 1 degree or less | Optional |
| Elimination of the effects of ocean and tidal currents | Difference between speed over ground and that through water | Calculated as the difference of each mean | 0.5 knot or less (absolute value) | Mandatory |
| Elimination of ice sea areas | Water temperature | Mean | 2 degrees or more | Optional |
| | Longitude Latitude | Mean | Based on ship position | Optional |
| Elimination of shallow water areas | Water depth | Mean | | Optional |
| | Longitude Latitude | Mean | Based on ship position | Optional |

The flowchart of the analysis and evaluation of ship performance in calm seas is shown in Fig. 3. Data extraction of the displacement from a data set is carried out the displacement within ± 5% of the set displacement, and the correction based on the admiralty coefficient is performed. To reduce the data variations, filtering conditions related to winds, waves, etc. is carried out before the evaluation of ship performance in calm seas. The criteria for stability and steadiness of data acquisition are listed in Table 4. If the data validation cannot be carried out in accordance with Table 3, the data filtering by the apparent slip ratio is performed[7), 8), 9), 10)].

Evaluation of ship performance in calm seas from the onboard monitoring is performed by Resistance Criteria Method (RCM) or the power-curve derived from tank tests.

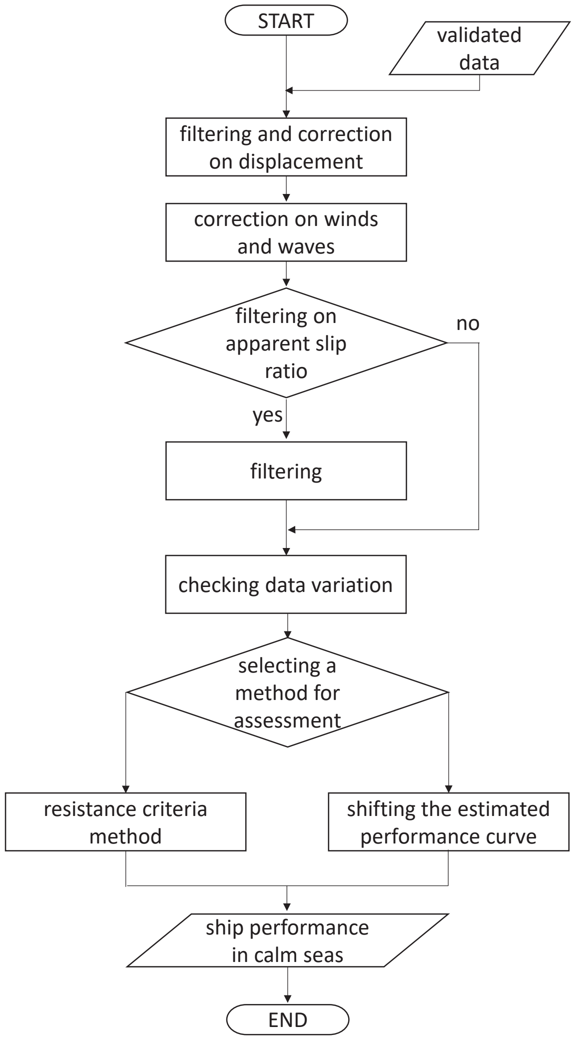



Fig. 3 Flowchart of the analysis and evaluation of ship performance in calm seas.

In relation to the correction of wave effect of onboard monitoring data accuracy of the radius of gyration is important. Estimation equations of radius of gyration have been prepared[11)].

Combined the approximate formula for the rolling period in International Code on Intact Stability[12)] as shown in Eqs. (1) and (2) with the relation between the rolling period and the lateral radius of gyration $K_{xx}$ as shown in Eq. (3), the lateral radius of gyration can be estimated by Eq. (4), if there are no measured or calculated values.

$$T_\phi = \frac{2C \cdot B}{\sqrt{GM}} \tag{1}$$

with

$$C = 0.373 + 0.023\frac{B}{d} - 0.043\frac{L_{wl}}{100} \tag{2}$$

$$T_\phi = \frac{2\pi K_{xx}}{\sqrt{gGM}} \tag{3}$$

$$K_{xx} = \frac{\sqrt{\pi}}{g} C \cdot B \tag{4}$$

The longitudinal radius of gyration $K_{yy}$ can be estimated by Eq. (5) to (7) if there are no measured or calculated values.

$$K_{yy} = \begin{cases} aL_{PP} + b & \text{for 4 ship types} \\ 0.25L_{PP} & \text{otherwise} \end{cases} \tag{5}$$

where

$$b = C_1 x + C_2 \tag{6}$$

$$x = \frac{\Delta_{ope}}{\Delta_{des}} \tag{7}$$

Coefficients $a$, $C_1$, and $C_2$ in Eqs. (5) and (6) are derived by the regression analysis of 104 ships of container ships, pure car carriers, bulk carriers and tankers. The coefficients for container ships, pure car carriers, bulk carriers and tankers are as shown in Table 5.

Table 5 Coefficients for estimation of longitudinal radius of gyrational.

| Ship type | $a$ | $C_1$ | $C_2$ |
|---|---|---|---|
| Container ship | 0.240 | -4.3 | 6.6 |
| Pure car carrier | 0.240 | -17.5 | 20.0 |
| Bulk carrier | 0.250 | -9.2 | 9.2 |
| Tanker | 0.235 | -11.2 | 13.1 |

The yaw radius of gyration $K_{zz}$ can be estimated by Eq. (8) if there are no measured or calculated values.

$$K_{zz} \approx K_{yy} \tag{8}$$

**3.2 Recommended Guidelines for CFD Calculations to Estimate Wind Forces in Actual Seas**

For the purpose of estimating the wind forces and moment of the superstructure, the recommended guidelines for the CFD calculations to estimate wind forces and moment have been established through the validation. CFD software used in the study is NAGISA[13].

CFD calculation is considered to be used at the design and development stage, and it is necessary to assume that there are severe restrictions on cost and time. Thus, the guidelines are summarized as considering the balance between ensuring accuracy and practical convenience[14].

The validity of the guidelines was carried out by the wind tunnel tests for a bulk carrier (JBC; Japan Bulk Carrier, a typical cape size bulk carrier), a PCC, a chemical tanker, and a container ship of full and ballast conditions.

The result is compared with that of wind tunnel tests and the regression formula from the ship dimensions[15]. The coefficients of longitudinal force, lateral force and yaw moment due to wind of JBC are shown in Fig. 4. Here $C_X$, $C_Y$, $C_N$ are the non-dimensional coefficients of longitudinal force, lateral force and yaw moment due to wind and defined as Eq. (9) to (11) by using the representative wind speed $U_w$ defined in Eq. (13), respectively. From the figure it is observed that CFD calculation based on the guidelines estimates with accuracy. The flow field by CFD calculation in head winds of JBC is shown in Fig. 5 as an example.

$$C_X = \frac{X_{wind}}{0.5\rho_A U_w^2 A_T} \tag{9}$$

$$C_Y = \frac{Y_{wind}}{0.5\rho_A U_w^2 A_L} \tag{10}$$

$$C_N = \frac{N_{wind}}{0.5\rho_A U_w^2 A_L L_{OA}} \tag{11}$$

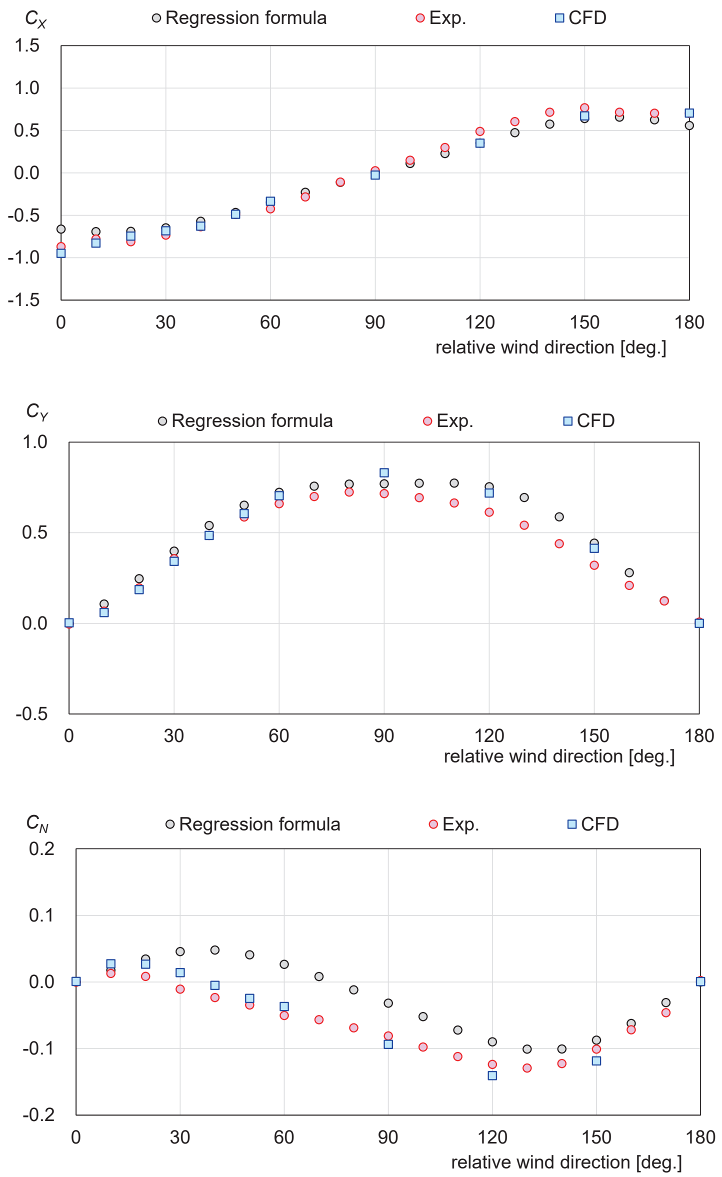



Fig. 4 Coefficients of longitudinal force (top), lateral force (middle) and yaw moment (bottom) due to wind of JBC.

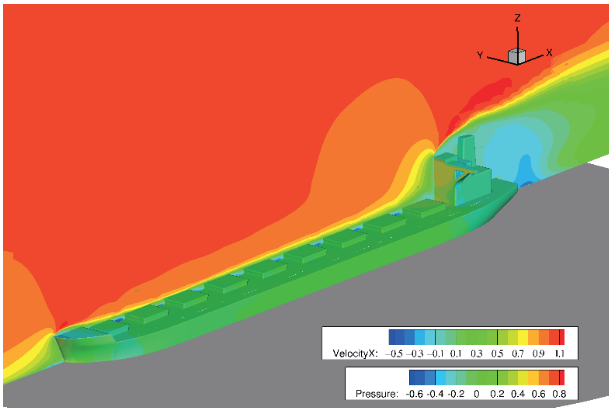



Fig. 5 An example of flow field by CFD calculation in head winds of JBC.

### 3.3 Recommended Guidelines for CFD Calculations to Estimate Resistance Increases due to Head Waves

As well as the CFD calculations to estimate wind forces and moment, the recommended guidelines for the CFD calculations to estimate added resistance in head waves have been established through the validation. CFD software used in the study is NAGISA.

The guidelines are summarized as considering the balance between ensuring accuracy and practical convenience[16)].

The consideration of the surge motion is important to save cost and time. The examinations were carried out by the tank tests in waves of JBC as shown in Fig. 6. The non-dimensional coefficient of added resistance in regular waves is defined as as Eq. (12). It shows that the effect of surge motion to the added resistance are within the measurement error range. As a result, the guidelines recommend that surge calculation is not required for the purpose.

From the examinations that CFD calculation based on the guidelines estimates with accuracy. The wave height distribution by CFD calculation in head waves of $\lambda/L_{PP} = 1.1$ of JBC is shown in Fig. 7 as an example.

$$K_{AW} = \frac{R_{AW}}{4\rho g \zeta_a^2 B^2 / L_{PP}} \tag{12}$$

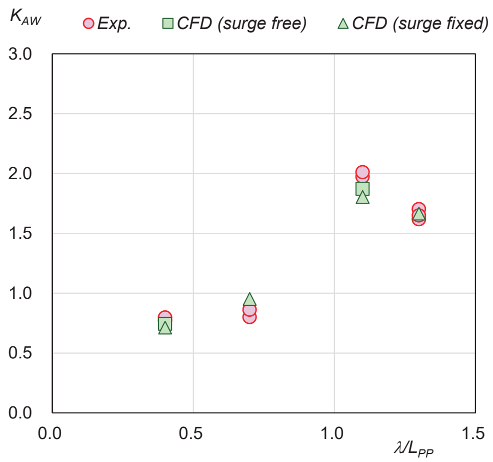



Fig. 6 Effect of surge motion to added resistance in regular head waves of JBC.

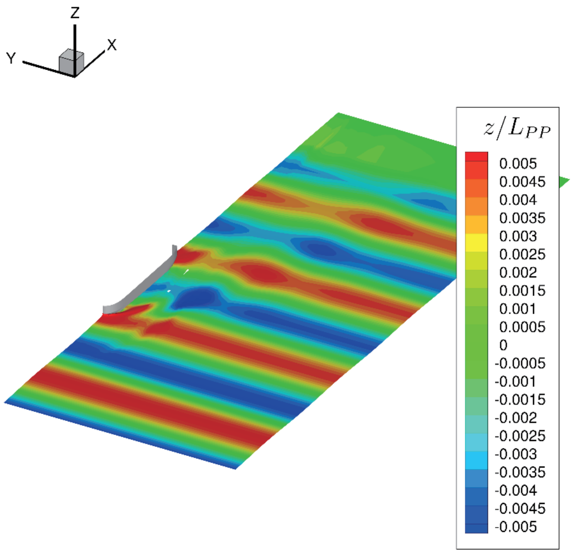



Fig. 7 An example of wave height distribution by CFD calculation in head waves of JBC ($\lambda/L_{PP}$ = 1.1).

### 3.4 Recommended Guidelines for Wind Tunnel Test to Estimate Ship Performance in Actual Seas

The recommended procedure for wind tunnel test is established based on the results of the round robin tests of wind force measurement using a bulk carrier and the measurements by four conditions of three types of ships. The ship type is listed here.

(a) Container ship (full load condition)
(b) Container ship (ballast condition)
(c) Pure car carrier
(d) Bulk carrier (JBC)
(e) Chemical tanker (33CT, a typical 33,000 DWT chemical tanker)

Model size is prescribed in the guidelines that the upper limit of the model size is 5% blockage ratio of the flow section in the wind tunnel[17]. And to confirm whether the measured wind force is not affected by Reynolds number, it is required that the change in the wind force coefficients is checked by three or more wind speeds at typical wind direction, such as 0 deg. or 90 deg.. The Reynolds number to be tested should be as high as possible above $1.0 \times 10^6$ when the length is taken as the length of the model.

For the data analysis, the definition of representative wind speed, $U_w$, is important for securing accuracy. Through the examinations based on the wind tunnel tests and deliberations of the technical committee on Ships in Operation at Sea, International Towing Tank Conference, the representative wind speed is defined as height average wind speed[18]. The conceptual diagram of the height average wind speed is shown in Fig. 8. The representative wind speed by height average wind speed is expressed in Eq. (13) to (16)[19), 20)].

$$U_w = \begin{cases} U_{A1} & \text{for } C_X \\ U_{A2} & \text{for } C_Y \text{ and } C_N \end{cases} \tag{13}$$

where

$$U_{A1}{}^2 = \frac{1}{H_{BR}} \int_0^{H_{BR}} U(z)^2 \, \mathrm{d}z \tag{14}$$

$$U_{A2}{}^2 = \frac{1}{H_L} \int_0^{H_L} U(z)^2 \, \mathrm{d}z \tag{15}$$

$$H_L = \frac{A_L}{L_{OA}} \tag{16}$$

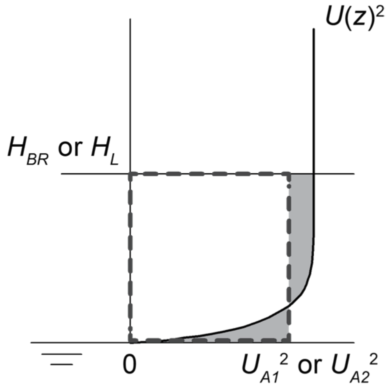



Fig. 8 Conceptual diagram of the height average wind speed.

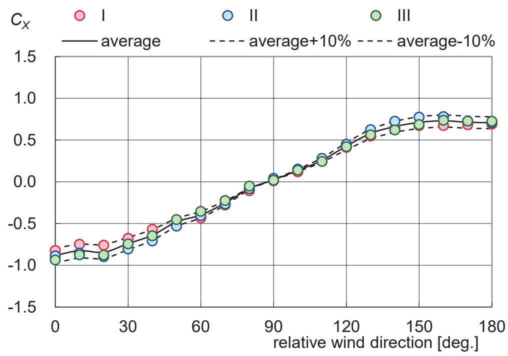



Fig. 9 Results of round robin tests of wind force measurement of JBC.

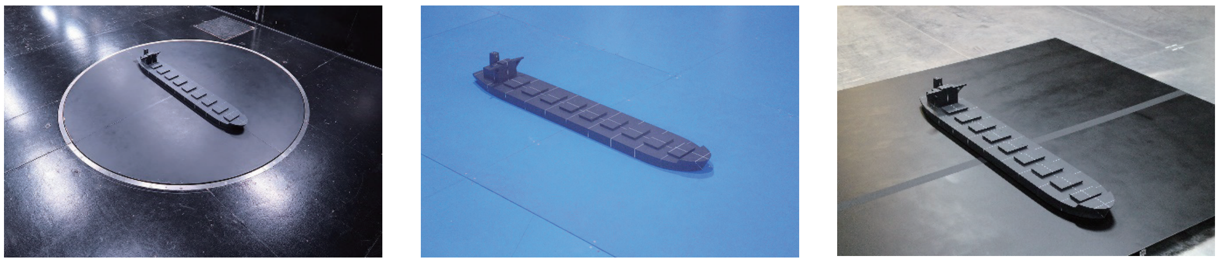


Fig. 10 Round robin tests of wind force measurements for JBC.

Results of the round robin tests for JBC are shown in Fig. 9 and 10. From the round robin tests the variation of the facilities on the longitudinal wind force is derived to 10%. The tested Reynolds number is $2.02\times10^6$ with the length of the ship model is 1.2 m.

### 3.5 Recommended Guidelines for Tank Tests in Waves to Ship Performance in Actual Seas

The guidelines for tank tests in waves describe the test conditions required to obtain a certain level of accuracy in both the resistance tests and the load varying tests in regular waves for all directions.

The tank tests were carried out for a bulk carrier (JBC), a container ship (DTC; Duisburg test case, a typical 14000 TEU container ship) and a chemical tanker (33CT). The large model with a length of over 6 m was used for the validation of added resistance and self-propulsion factors in head waves, medium size model with a length around 4.5 m was used for the validation of added resistance and self-propulsion factors in directional waves and the small model with a length around 3 m was used for the round-robin tests for added resistance in directional waves.

Round robin tests in regular waves were carried out for JBC and DTC by the OCTARVIA project as shown in Fig. 11.

Along with the validation by the round robin tests[21)], the guidelines have been established by referring the ITTC Recommended Procedures and Guidelines[22), 23), 24), 25)] and Guidelines[26)], and the practices of each participating company.

The result of the round robin tests for added resistance in regular waves are shown in Fig. 12. Here "A", "a", "i" etc. in the legend represent each institute. The same symbol in the paper represents the same institution.

Two methods of load varying test are prescribed in the guidelines. One is Adachi method[27)] and the other is the British method[28)], both of which are used for the analysis of self-propulsion factors in regular waves. The results of the round robin tests for load varying tests in still water and regular head waves of JBC and DTC are shown in Fig. 13 and Fig. 14, respectively.

Fig. 14 shows change of the wake coefficient by the influence of incident waves and ship motion ($\Delta U_{a0wc}$). It can be seen that $\Delta U_{a0wc}$ has a frequency response.

Fig. 11(a) Round robin test in waves of JBC.

Fig. 11(b) Round robin test in waves of DTC (large model).

Fig. 11(c) Round robin test in waves of DTC (small model).

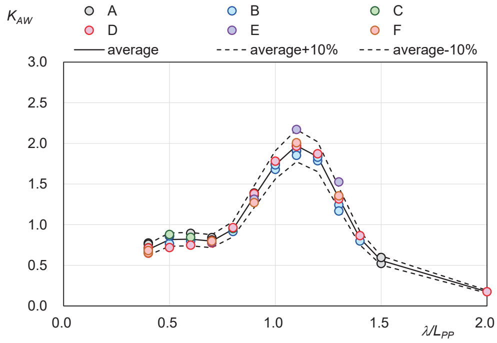



Fig. 12(a) Added resistance in regular head waves of JBC, *Fr*=0.142.

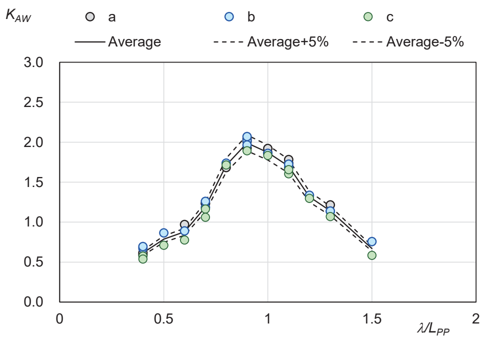



Fig. 12(b) Added resistance in regular head waves of DTC (large model), *Fr*=0.157.

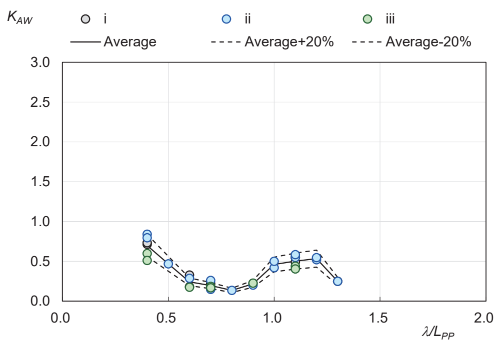



Fig. 12(c) Added resistance in regular beam waves of DTC (small model), *Fr*=0.157.

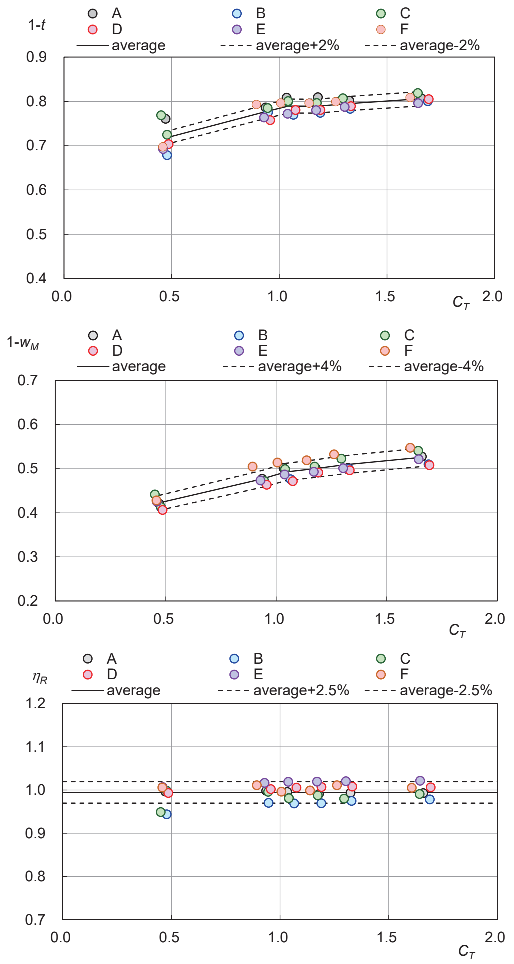



Fig. 13(a) Self-propulsion factors in still water of JBC (thrust deduction coefficient (top), wake coefficient (middle) and relative rotative efficiency (bottom)), $Fr$=0.142.

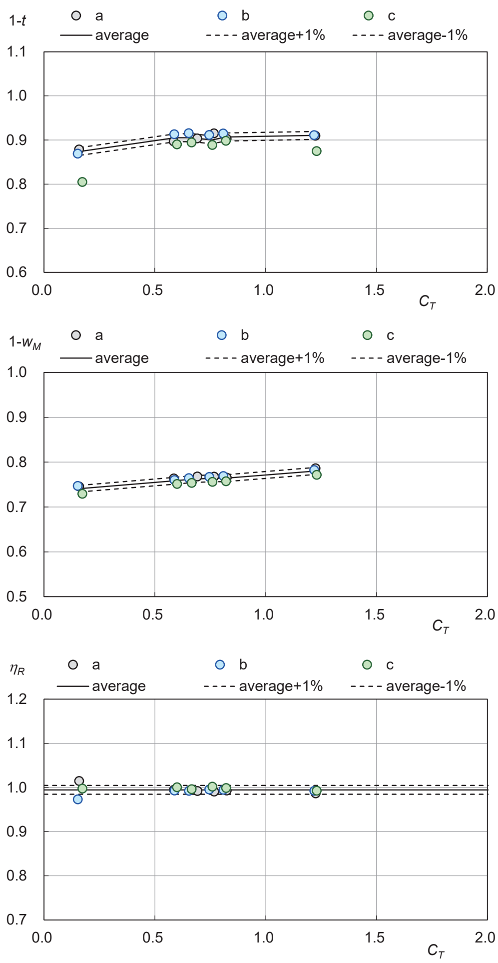



Fig. 13(b) Self-propulsion factors in still water of DTC (thrust deduction coefficient (top), wake coefficient (middle) and relative rotative efficiency (bottom)), $Fr$=0.157.

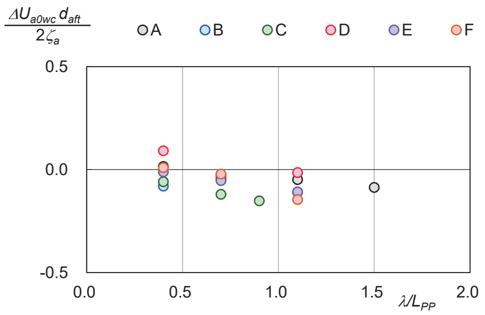



Fig. 14(a) Change of the wake coefficient by the influence of incident waves and ship motion ($\mathit{\Delta} U_{a0wc}$) in regular head waves of JBC, $Fr$=0.142.

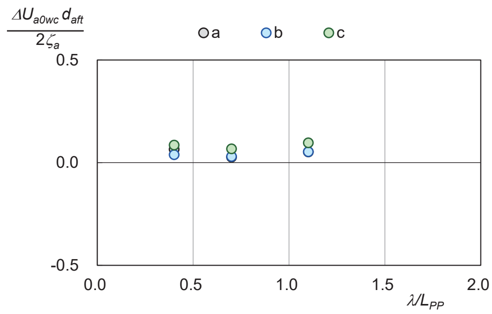



Fig. 14(b) Change of the wake coefficient by the influence of incident waves and ship motion ($\mathit{\Delta} U_{a0wc}$) in regular head waves of DTC, $Fr$=0.157.

From the round robin tests, it was quantitatively found that the added resistance in waves and self-propulsion factors vary depending on the facilities and test instruments.

In the guidelines test conditions are prescribed in the viewpoint of accuracy tests. The standard wave height of the tank test is set to an equivalent of 3 m for the full scale ship where assuming the performance evaluation under average weather conditions in ocean, and can be reduced to 1/100 of the ship length if necessary.

For Adachi method, the measurements are planed under three or more propeller load conditions. The propeller load setting range is approximately ± 30% of the ship self-propulsion point in waves.

For British method, the measurements are planned under two or more propeller load conditions across the ship self-propulsion point in waves. The propeller load setting range is approximately ± 10% of the ship self-propulsion point in waves.

**3.6 Recommended Guidelines for Tank Test Analysis in Waves to Ship Performance in Actual Seas**

The guidelines prescribe the analysis methods of the tank tests carried out accordance with "Recommended Guidelines for Tank Tests in Waves to Ship Performance in Actual Seas".

The guidelines explain the analysis method to obtain the coefficient of advance speed required to perform NMRI method[29] for added resistance in waves and the analysis method of load varying tests for both Adachi method and British method.

The analysis method of Adachi method is shown in Eq. (17) to (20).

$$C_T = \frac{T_M}{\frac{1}{8}\pi\rho D_{PM}{}^2 V_M{}^2} \tag{17}$$

$$1 - w_M = U_{a0} + C_0\left(-U_{a0} + \sqrt{C_T + U_{a0}{}^2}\right) \tag{18}$$

$$C_G = \frac{R_{TM}(T) + T_M - R_{Cw}}{\frac{1}{8}\pi\rho D_{PM}{}^2 V_M{}^2} = B_0\left(-U_{a0} + \sqrt{C_T + U_{ao}{}^2}\right) \tag{19}$$

$$1 - t = 1 - \frac{C_G}{C_T} \tag{20}$$

$R_{Cw}$ is obtained by interpolating the measured hull resistance at 0 thrust. The coefficients of $B_0$, $C_0$ and $U_{a0}$ are obtained by the load varying tests in still water using the least-squares method.

For the relative rotative efficiency, $\eta_R$, the value at the ship self-propulsion point in still water is also used for the value in waves.

The change in (1-$w_M$) due to hull motion in waves can be taken into account by adding the difference between the values in waves and these in still water to $U_{a0}$ in Eq. (18).

The analysis method of British method is shown in Eq. (21) to (26).

$$1 - t = \frac{R_{TM} - F_D}{T_M} \tag{21}$$

$$V_{AM} = J_M n_M D_{PM} \tag{22}$$

$$1 - w_M = \frac{V_{AM}}{V_M} \tag{23}$$

$$\eta_{oM} = \frac{J_M K_{TM}(J_M)}{2\pi K_{QM}(J_M)} \tag{24}$$

$$\eta_{BM} = \frac{T_M V_{AM}}{2\pi n_M Q_M} \tag{25}$$

$$\eta_R = \frac{\eta_{BM}}{\eta_{oM}} \tag{26}$$

The self-propulsion factors at the ship self-propulsion point in waves are given as a linear interpolation by the least square method of each self-propulsion factor at the point where the towing force $F_D$ equals to the skin friction correction.

Besides, correction for the effects of gravity and inertial force on propeller thrust measurements using the ship vertical motion[30) is described as informative.

### 3.7 Recommended Guidelines for Estimating Ship Performance in Actual Seas

Validation by model tests and by full scale ships were carried out, and the guidelines for estimation method on ship performance in actual seas were established. The guidelines provide the standard method on short-term prediction of the ship propulsive performance (ship speed, engine output, engine rate of revolution) in actual seas to the practice of ship design, development, construction, and operation planning[31), 32), 33)]. The flowchart of ship performance estimation in actual seas is shown in Fig. 15.

To estimate load varying effects on self-propulsion factors, two types of estimation models (OCTARVIA-1 method and OCTARVIA-2 method) are prescribed. OCTARVIA-1 method is based on momentum theory by Adachi method and OCTARVIA-2 method is the function fitting of measured data. Both are available so that users can select a method which suits their practical needs.

For OCTARVIA-1 method estimation of self-propulsion factors considering propeller load is formulated based on the momentum theory. The method expresses (1-$w_M$) and (1-$t$) as a function of $C_T$ by Eq. (27) to (30). The difference between the self-propulsion factors at the ship self-propulsion point in still water and these in waves is added to the self-propulsion factors in still water based on $R_0$, resistance without a propeller in still water. The self-propulsion factors in waves are redefined, but this treatment is consistent with the test practice. One of the merits of OCTARVIA-1 method is that it can take into account the changes of the wake coefficient by the influence of incident waves and ship motion, $\Delta U_{a0wc}$, for the estimation[34)]. However, $\Delta U_{a0wc}$ is treated as 0 tentatively, since it is necessary to further validation for many ship types.

Estimation of the load varying parameters of $B_0$, $C_0$, and $U_{a0}$ is required for the performance estimation at design stage, but the estimation formulae for $B_0$, $C_0$, and $U_{a0}$ are prepared.

For $\eta_R$ at the ship self-propulsion point in waves, the value at the ship self-propulsion point in still water is used as Eq. (31).

$$1-w_M = U_{a0wc} + C_0(V)\left(-U_{a0wc} + \sqrt{C_T + U_{a0wc}^{\ 2}}\right) \tag{27}$$

$$U_{a0wc} = U_{a0}(V) + \Delta U_{a0wc}(H, T, \theta, V) \tag{28}$$

$$C_G = \frac{R_T(T) + T - R_{Cw}}{\frac{1}{8}\pi\rho D_P^{\ 2} V^2} = B_0(V)\left(-U_{a0}(V) + \sqrt{C_T + U_{ao}(V)^2}\right) \tag{29}$$

$$1-t = 1-\frac{C_G}{C_T} \tag{30}$$

$$\eta_R = \eta_{R,SW}(V) \tag{31}$$

$C_T$ in the weather condition is given to Eq. (32).

$$C_T = \frac{1}{2}\left[B_0\left\{\left(B_0 - 2U_{a0}\right) + \sqrt{\left(B_0 - 2U_{a0}\right)^2 + 4C_{RC}}\right\} + 2C_{RC}\right] \tag{32}$$

with

$$C_{RC} = \frac{8\left(R_{Cw} - SFC\right)}{\pi\rho D_P{}^2 V^2} \tag{33}$$

For OCTARVIA-2 method estimation of self-propulsion factors considering propeller load is formulated based on the fitting of the experiment data and is similar to the JTTC method[35]. The difference between the OCTARVIA-2 method and the JTTC method is the influence of the propeller load on the self-propulsion factors.

Two fitting methods are available for OCTARVIA-2 method; linear type fitting for $C_T$ and square root type fitting for $C_T$. These methods are shown in Eq. (34) to (37) and in Eq. (38) to (41), respectively.

1) Linear type fitting method for $C_T$

$$(1-t)(V, C_T) = a_{t,1}^{BM}(V)C_T + b_{t,1}^{BM}(V) = (1-t)_{SW}(V) + a_{t,1}^{BM}(V)\Delta(C_T) \tag{34}$$

$$(1-w_M)(V, C_T) = a_{w,1}^{BM}(V)C_T + b_{w,1}^{BM}(V) = (1-w_M)_{SW}(V) + a_{w,1}^{BM}(V)\Delta(C_T) \tag{35}$$

$$\eta_R(V) = \eta_{R,SW}(V) \tag{36}$$

$$\Delta(C_T) = C_T - C_{T,SW}(V) \tag{37}$$

Here, $a_{t,1}^{BM}$ , $b_{t,1}^{BM}$ ,  $a_{w,1}^{BM}$ ,  $b_{w,1}^{BM}$  are the constants of (1-$t$) and (1-$w_M$), respectively.

2) Square root type fitting method for $C_T$

$$(1-t)(V, C_T) = a_{t,2}^{BM}(V)\sqrt{C_T} + b_{t,2}^{BM}(V) = (1-t)_{SW}(V) + a_{t,2}^{BM}(V)\Delta(\sqrt{C_T}) \tag{38}$$

$$(1-w_M)(V, C_T) = a_{w,2}^{BM}(V)\sqrt{C_T} + b_{w,2}^{BM}(V) = (1-w_M)_{SW}(V) + a_{w,2}^{BM}(V)\Delta(\sqrt{C_T}) \tag{39}$$

$$\eta_R(V) = \eta_{R,SW}(V) \tag{40}$$

$$\Delta(\sqrt{C_T}) = \sqrt{C_T} - \sqrt{C_{T,SW}(V)} \tag{41}$$

Here, $a_{t,2}^{BM}$ , $b_{t,2}^{BM}$ ,  $a_{w,2}^{BM}$ ,  $b_{w,2}^{BM}$  are the constants of (1-$t$) and (1-$w_M$), respectively.

$C_T$ in the weather condition is given by Eq. (42) using iterative calculation.

$$C_T = \frac{R_T}{(1-t)(V, C_T)} \frac{8}{\pi\rho D_P{}^2 V^2} \tag{42}$$

Besides, the performance estimation for ships having controllable pitch propeller is included in the guidelines.

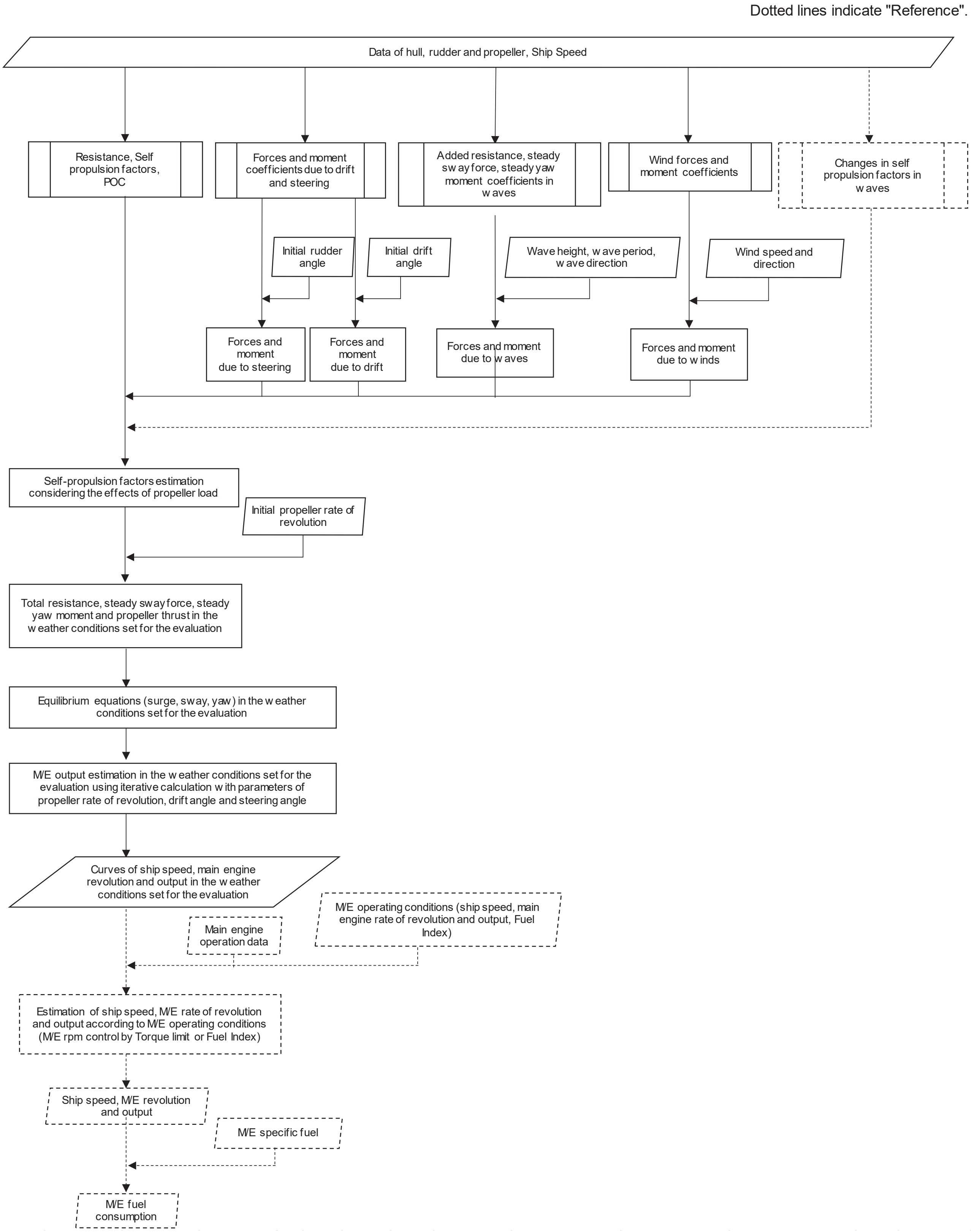



Fig. 15 Flowchart of ship performance estimation in actual seas.

## 4. Calculation programs

Based on these guidelines, following three programs have been developed to calculate ship performance in actual seas.

In order to estimate performance in actual seas, it is necessary to estimate steady forces in waves, wind forces, rudder forces, drift forces, and change of propulsion efficiency due to load variation.

Regarding steady forces in waves, the calculation of added resistance in waves is particularly important. NMRI method, which is addressed to be the most accurate practical calculation method in the comparative study by ITTC[36), 37)] is implemented in the program. In addition, in the program, the accuracy improvement in following waves[32)] and a term of the rolling motion on added resistance in waves[33)] are added. For steady sway force and yaw moment in waves of a ship having advancing speed are formulated by using the ship wave theory[38)], however, these have not been well validated experimentally and numerically. Therefore, a three-dimensional calculation using the singularity distribution of zero forward speed is used for the estimation[39), 40)]. For the wind forces, the regression formulae by Fujiwara et al., which are regarded as the most accurate practical calculation method in the comparative study by ITTC[36)], are implemented. The rudder forces are estimated by the regression formulae using the ship dimensions[41), 42)]. The drift forces are estimated by regression formulae using the ship dimensions[43)], but the induced resistance due to the small aspect ratio is implemented in the estimation of the longitudinal drift force[44)]. The propulsion efficiency is estimated by the change of the propeller efficiency due to the propeller load, and the changes of the self-propulsion factors are implemented as an option of the calculation. The decrease of ship speed and the fuel consumption are calculated considering the operating limit of the main engine and the operating of the engine governor[32)].

The prediction accuracy of the fuel consumption by the estimation method is validated by using RCM to be within ±2.0%[9), 10)].

### 4.1 Evaluation of Ship Performance in Actual Seas

The calculation program "OCTARVIA-web" for predicting and evaluating of ship performance in actual seas is opened to the public via NMRI Cloud service. The program predicts ship performance in actual seas based on "Recommended Guidelines for Estimating Ship Performance in Actual Seas" and evaluates the life cycle fuel consumption. Inputs of the program are the standard operational model and ship performance for an individual ship. The standard operational model consists of route, season, direction of sailing, loading condition, designated ship speed, rate of operating days per year, rate of aging deterioration, rate of biological fouling, timing of cleaning, and evaluation period. Outputs of the program are total fuel consumption, and averaged fuel consumption per day as the life cycle fuel consumption, and total amount of cargo, total distance of transport work, and fuel consumption per ton NM as the transport efficiency[45)]. Fig. 16 shows prediction of power curves and fuel consumption in actual seas for an example of a container ship, where EC is the evaluation condition of weather. EC was determined by the investigation of encounter weather measured by the ships. Compared to the Beaufort scale of wind[46)], which has been commonly used for ship operators, the significant wave height $H$ of EC sets one rank higher than the wave height of the Beaufort scale of wind against the same wind speed $V_w$. The mean wave period $T_{01}$ sets by the empirical relation between the significant wave height $H$ as shown in Eq. (43) which assumed fully developed waves in the ocean. An example output of the life cycle fuel consumption is shown in Fig. 17.

$$T_{01} = 3.86\sqrt{H} \tag{43}$$

The top menu of "OCTARVIA-web" is shown in Fig. 18.

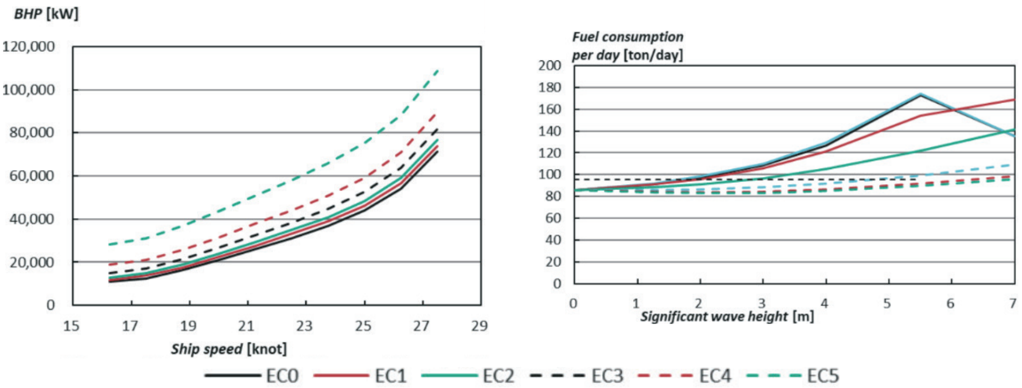
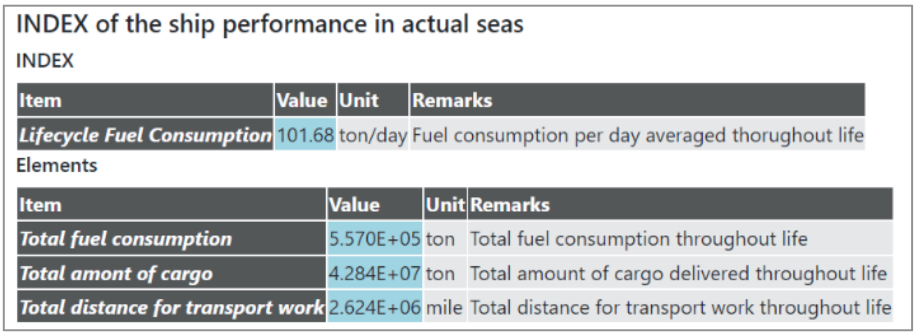



Fig. 16(a) Prediction of power in actual seas (a container ship in head winds and waves).

Fig. 16(b) Prediction of fuel consumption in actual seas (a container ship in head winds and waves).

Table 6 Evaluation conditions

| EC | Mean wind speed: $V_w$ [m/s] | Significant wave height: $H$ [m] | Mean wave period: $T_{01}$ [s] |
|---|---|---|---|
| 1 | 4.4 | 1.25 | 4.3 |
| 2 | 6.9 | 2.0 | 5.5 |
| 3 | 9.8 | 3.0 | 6.7 |
| 4 | 12.6 | 4.0 | 7.7 |
| 5 | 15.7 | 5.5 | 9.1 |
| 6 | 19.0 | 7.0 | 10.2 |


INDEX of the ship performance in actual seas

INDEX

| Item | Value | Unit | Remarks |
|---|---|---|---|
| Lifecycle Fuel Consumption | 101.68 | ton/day | Fuel consumption per day averaged thorughout life |

Elements

| Item | Value | Unit | Remarks |
|---|---|---|---|
| Total fuel consumption | 5.570E+05 | ton | Total fuel consumption throughout life |
| Total amont of cargo | 4.284E+07 | ton | Total amount of cargo delivered throughout life |
| Total distance for transport work | 2.624E+06 | mile | Total distance for transport work throughout life |

Fig. 17 Life cycle fuel consumption (a container ship).

**4.2 Monitoring Data Analysis**

The calculation program "SALVIA-OCT.-web" for analyzing the onboard monitoring data is opened to the public via NMRI Cloud service. The program analyzes the data based on "Recommended Guidelines for Onboard Monitoring". The feature is that it is possible to analyze onboard monitoring data without arbitrariness. The top menu is shown in Fig. 19.

**4.3 Estimation the hull form and the calm sea performance from the principal dimensions**

The calculation program "EAGLE-OCT.-web" for estimating the hull form and the calm sea performance from the principal dimensions is opened to the public via NMRI Cloud service. These data are required for the input of "OCTARVIA-web" and "SALVIA-OCT.-web". Using the program, even shipping company users who do not have detailed hull data can evaluate the ship performance in actual seas.

The top menu is shown in Fig. 20

Each program operates in cooperation with input and output. The relation is shown in Fig. 21.

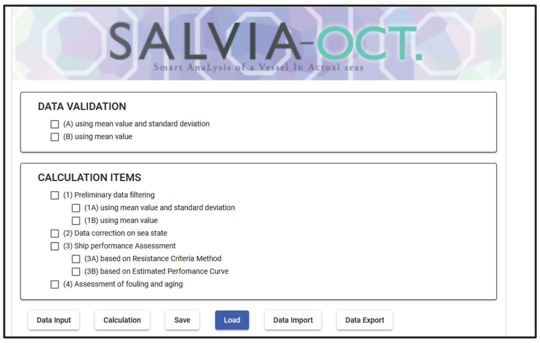



Fig. 19 Top menu of SALVIA-OCT.-web.

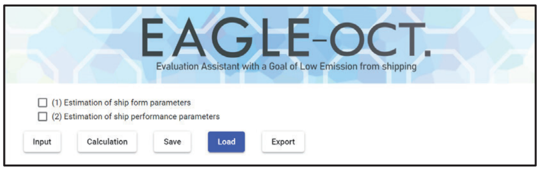



Fig. 20 Top menu of EAGLE-OCT.-web.

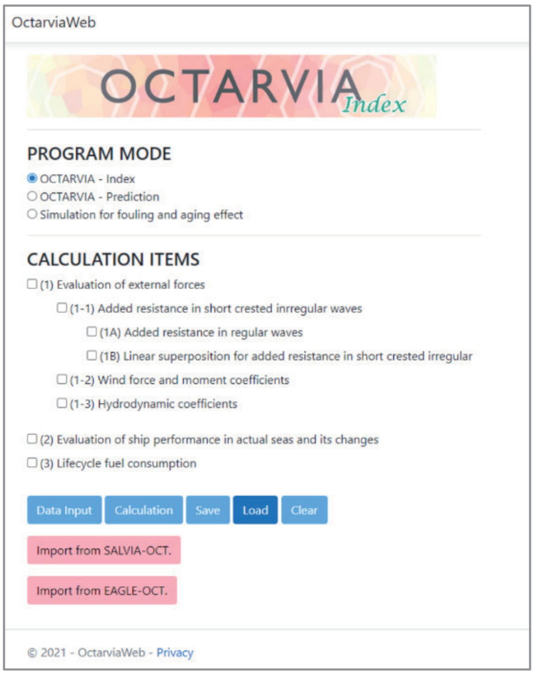



Fig. 18 Top menu of OCTARVIA-web.

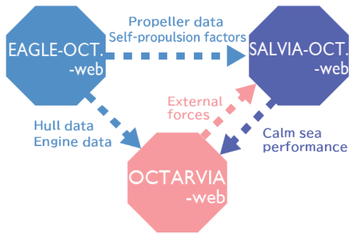



Fig. 21 Program cooperation.

## 5. Conclusions

Digitalization is progressing in the maritime industries and monitoring system is being implemented onboard. It is considered that digitization, if used properly, can bring transparency and fairness to the business. But it is not easy to draw out the right information to make a decision, since the big data contain uncertain factors such as weather conditions and manoeuvring operation.

In OCTARVIA project, seven recommended guidelines are established and three calculation programs are developed and these contents are shown.

By combining the prediction method of ship performance in actual seas prescribed in the guidelines and the monitoring data analysis method of full scale ship prescribed in the guidelines, anyone can validate the ship performance in actual seas with high transparency.

By using these programs which implement the recommended guidelines, anyone can evaluate ship performance in actual seas with the same accuracy.

Using the results of OCTARVIA project, impact of high performance ships/devices on the ship building, impact of ship operation by the high performance ships/devices, impact of early docking on the maintenance, etc. can be evaluated. The use of the results is expected to bring a lot of benefits to stakeholders.

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