Validation of Filtering Method for Evaluating Ship Performance in Calm Sea Using Onboard Monitoring Data

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Summary

Evaluation of ship performance in actual seas is important for reduction of greenhouse gas emissions from the shipping sector. Recently, activities to investigate ship performance by means of onboard monitoring have become increasingly widespread. While onboard monitoring can collect a vast amount of data, it is necessary to follow a proper procedure for an accurate evaluation of ship performance.

Prior to this study, the authors proposed a filtering method called the Resistance Criteria Method (RCM) with the aim of extracting onboard monitoring data collected in a calm sea, in which the rate of added resistance is a key parameter. This study addresses validation of RCM using onboard monitoring data of a panamax container ship and a medium range tanker. The validation was carried out by comparing the ship speed and fuel consumption in the onboard monitoring data and a voyage simulation using the evaluated performance based on the conventional method and RCM as an input. The results showed that application of RCM is effective for evaluating ship performance based on onboard monitoring data.

1. Introduction

Recently, onboard monitoring has been widely conducted in order to evaluate ship performance in service. The International Maritime Organization (IMO) started the Data Collection System (DCS) for fuel consumption on January 2019 as a measure for a greenhouse gas (GHG) reduction strategy. These developments show that onboard monitoring is becoming a significant trend and requires an accurate method for evaluating ship performance based on onboard monitoring data.

Evaluation methods based on onboard monitoring data include ISO 19030¹, which stipulates procedures for measuring changes in hull and propeller performance such as data validation, data filtering, and data collection. ISO 19030 neither aims to compare the performance between different ships including sister ships nor to treat wave correction. ISO 19030 also recommends that the wind speed should be less than 7.9 m/s in order to filter data measured in a calm sea. In general, both winds and waves influence ship performance, and the degree of influence depends on the ship size. Therefore, more reasonable criteria for data filtering, which can consider ship size, are required.

The authors developed the Resistance Criteria Method (RCM)² to satisfy this requirement. RCM introduces an increase rate of resistance in actual seas as a parameter for filtering to enable a robust and uniform evaluation of the ship performance.

RCM also includes an apparent slip ratio in order to eliminate deviating data and ensure the reliability of the evaluated performance.

This study addresses the validation of RCM using onboard monitoring data and demonstrates that RCM is more effective for filtering than conventional methods. In this validation, ship performance in a calm sea is evaluated by the conventional methods and RCM and is then used in a voyage simulation, which is compared with the onboard monitoring data.

2. Onboard Monitoring Data

This study deals with onboard monitoring data of a panamax container ship (PCS) and a medium range tanker (MRT) whose principal particulars are shown in Table I. The representative displacement (Δrep) in operation is determined as summarized in Table 2 based on the voyage record, where Δdes denotes the displacement in the design full condition.

Table 1 Principal particulars of subject ships.

| Ship type    | Container | Tanker |
|--------------|-----------|--------|
| Ship ID      | PCS       | MRT    |
| Length       | 270.0 m   | 185.0 m|
| Breadth      | 35.0 m    | 32.2 m |
| Design draft | 12.0 m    | 13.0 m |

Table 2 Representative displacement.

| Ship ID | Group ID | Displacement | Number of voyages |
|---------|----------|--------------|-------------------|
| PCS     | G1       | 93% Δdes     | 4                 |
|         | G2       | 102% Δdes    | 5                 |
| MRT     | G1       | 80% Δdes     | 2                 |
|         | G2       | 51% Δdes     | 4                 |

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Received 3 December 2020
The main sea area of PCS and MRT is North Pacific Ocean. The period for collecting onboard monitoring data is one year and the sea condition in which the data is collected include calm and rough seas for both the ships. Sampling interval of the onboard monitoring data is 30 minutes for PCS and one hour for MRT. Wind data and performance data such as the ship speed are auto-logged, while draft and displacement data are recorded at departure and arrival.

Since the two ships are not equipped with an instrument for measuring waves onboard, hindcast data provided by the Japan Weather Association is incorporated in the monitoring data.

3. Resistance Criteria Method

3.1 Preprocessing of RCM

Preprocessing prior to RCM consists of two processes; one is filtering to ensure a steady state and the other is correction of the engine revolution and power for the effects of winds and waves. The former aims to obtain data measured in a steady state, for example, a situation in which a ship navigates with a constant speed. Specifically, this means filtering by rudder angle, drift angle, engine revolution, and the speed difference between the ship speed through water and that over ground. At the same time, filtering by displacement is conducted to extract data measured at a displacement which is within ±5% of the representative displacement.

The latter aims to obtain the engine revolution and power in a calm sea considering the effect of winds and waves, which is different from ISO 19030 and is advantageous for obtaining an accurate evaluation. In this study, the added resistances in winds and in waves are calculated by a regression formula and a theoretical method with an empirical formula, respectively. Input data such as the hull form and superstructure parameters are estimated on the basis of the ship’s principal particulars.

Before the correction of the engine revolution and power, the ship speed through water measured during voyages is corrected to that for the representative displacement in accordance with the Admiralty coefficient.

3.2 Filtering by Apparent Slip Ratio

The first step of RCM is filtering by the apparent slip ratio (hereinafter, ASR) with the aim of eliminating data having less accuracy of the ship speed through water. To ensure the reliability of the evaluation, deviating data should not be used.

The apparent slip ratio $S_d$ is defined in eq. (1), where $V_S$ is ship speed through water, $P_p$ is propeller pitch, and $n_{id}$ is the engine revolution in a calm sea which is corrected for the effects of winds and waves.

$$S_d = 1 - \frac{V_S}{P_p n_{id}} \tag{1}$$

In the case that $N$ data have been preprocessed and $i$-th ASR is defined as $S_{Ai}$, the mean of ASR $\overline{S_d}$, $i$-th normalized ASR $\hat{S}_{di}$, and the standard deviation $\sigma_i$ of the normalized ASR are calculated as follows.

$$\overline{S_d} = \frac{1}{N} \sum_{i=1}^{N} S_{di} \tag{2}$$

$$\hat{S}_{di} = S_{di} - \overline{S_d} \tag{3}$$

$$\sigma_i = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \hat{S}_{di}^2} \tag{4}$$

Specifically, filtering by ASR means that the data satisfying eq. (5) are filtered. $C$ in eq. (5) is allowance factor for ASR.

$$\left| \hat{S}_{di} \right| \leq C \cdot \sigma_i \tag{5}$$

For an accurate evaluation of performance, it is necessary to assign an appropriate value to $C$. In order to find the appropriate $C$, the influence of $C$ on the relationship between the ship speed through water and the corrected engine revolution is investigated. Equation (1) can be transformed into eq. (6):

$$n_{id} = \frac{V_S}{(1 - S_{Ai})P_p} = s \cdot V_S \tag{6}$$

Equation (6) indicates that the corrected engine revolution is expressed as a linear function of the ship speed. The parameter $s$ is calculated for each of the data. The maximum and minimum of $s$ can be defined as $s_{max}, s_{min}$, respectively. For the investigation, the speed variation ratio $\delta V$ illustrated in Fig. 1 is defined, where $V_1$ and $V_2$ are the ship speed corresponding to $s_{max}, s_{min}$ at a constant revolution, respectively.

$$\delta V = \frac{V_2 - V_1}{\frac{1}{2}(V_1 + V_2)} = 2\left(\frac{s_{max} - s_{min}}{s_{max} + s_{min}}\right) \tag{7}$$

The relationship between $\delta V$ and $C$ is shown Fig. 2, which indicates that $\delta V$ follows the increase of $C$ in all cases. For an
accurate evaluation, it is preferable to assign a smaller value to $C$, but an extremely small $C$ may fail to provide a sufficient number of data after filtering by ASR.

![Graph of speed variation rate to $C$](image)

Fig. 2 Response of speed variation rate to $C$.

The number of data filtered by ASR is investigated in order to ensure that a sufficient number of filtered data is provided to the next step of RCM. Fig. 3 shows the rate of the number of filtered data, where $N_{fil}$ and $N_{all}$ mean the number of data filtered by ASR and the number of all preprocessed data, respectively. Based on the result of the investigation, the authors applied $C=1.0$ to keep $\delta V$ to less than 10% while extracting at least 65% of the preprocessed data.

![Graph of rate of number of filtered data](image)

Fig. 3 Rate of number of filtered data.

### 3.3 Filtering by Increase Rate of Resistance

The second step of RCM is filtering by the increase rate of resistance $\delta R$ in actual seas, which is defined as follows.

$$\delta R = \frac{\Delta R}{R_{ad}} \quad (8)$$

$$R_{ad} = R_{ms} - \Delta R \quad (9)$$

where $\Delta R$ is the increase of resistance due to winds and waves, and $R_{ad}$ and $R_{ms}$ are the resistance in a calm sea and that in actual seas, respectively. $R_{ad}$ and $R_{ms}$ are calculated in the process of the correction for the effects of winds and waves.

As filtering by $\delta R$ is explained in detail in Reference 2, only an outline is presented here. Filtering by $\delta R$ consists of two types of filtering. One is filtering to extract “evaluation data,” which are measured in seas equivalent to a calm sea. The other is filtering to extract “fitting data,” which are measured in winds and waves, although not under rough conditions. The aim of the latter filtering is to obtain data distributed over a wider range of engine revolutions. In this study, the criteria for the evaluation data $\delta R_{eval}$ and the fitting data $\delta R_{fit}$ are 2% and 100%, respectively. A performance curve called a “fitting curve” is obtained by applying the numerical model expressed by eq. (10) and eq. (11).

$$N_E = d_w \cdot V_S \quad (10)$$

$$P = a_n \cdot N_E^{b_n} \quad (11)$$

where $N_E$ and $P$ are the corrected engine revolution and power, respectively. An evaluation index $D_{PC}$ which expresses the variation in the evaluation data around the fitting curve is calculated by eq. (12)

$$D_{PC} = \sqrt{\frac{\sum_{i=1}^{N_{eval}} \left(d_{norm}(i)\right)^2}{N_{eval}}} \quad (12)$$

where $N_{eval}$ is the number of evaluation data and $d_{norm}$ is the normal distance between the evaluation data and the fitting curve which is illustrate in Fig. 4. In the figure, $V_{des}$ and $P_{mcr}$ are ship speed at the design condition and power at maximum continuous rate, respectively.

![Graph of d_{norm}](image)

Fig. 4 Definition of $d_{norm}$.

In reference to the study (3) by Sakurada et al., the $D_{PC}$ criterion of $C_{DPC}=2.0$ was adopted for the relationship between ship speed and engine power. Obtaining a $D_{PC}$ which is less than $C_{DPC}$ completes the filtering by $\delta R$ and thus the fitting curve is identified as the resultant performance in a calm sea. If $D_{PC}$ is not less than $C_{DPC}$, the fitting curve is redrawn using fitting data extracted by a decreased $\delta R_{fit}$, and $D_{PC}$ is calculated with the redrawn fitting curve iteratively until $D_{PC}$ satisfies $C_{DPC}$.

An example of an evaluation of ship performance in a calm sea by RCM is shown in Fig. 5 and Fig. 6 for PCS-G2. In this example $C=1.0$ in the filtering by ASR and $C_{DPC}=2.0$ is applied. Fig. 5 shows how the data are extracted by the filtering by ASR and demonstrates that this filtering is effective for decreasing the variation in preprocessed data. In $V_sN_E$ plane, $D_{PC}$ is decreasing from 1.63 to 0.88.
Fig. 5 Filtering by apparent slip ratio (PCS-G2).

Fig. 6 Filtering by increase rate of resistance and performance evaluation (PCS-G2).

Fig. 6 shows the fitting data and the evaluation data obtained in the filtering by the increase rate of resistance and the evaluated performance curve. In this case, \( D_{PC} \) in \( V_S-P \) plane is decreasing from 2.55 to 1.56, which satisfies the criterion for \( D_{PC} \). The coefficients \( a_n \), \( b_n \), \( d_n \) are 0.0528, 2.8992, 4.1434, respectively.

4. Validation

The authors previously conducted a validation\(^3\) of the effectiveness of RCM using the onboard monitoring data of a tanker. That validation indicated that filtering by ASR is effective for eliminating deviating data which seem to be measured in an unsteady state. RCM was also compared with other filtering methods, leading to the conclusion that RCM can give the smallest \( D_{PC} \) among the filtering methods.

For further validation, in this study, a voyage simulation was conducted using the ship performance evaluated by RCM and other filtering methods, and the results were compared with the onboard monitoring data.

4.1 Validation Cases

In order to demonstrate that RCM is superior to other filtering methods in terms of voyage simulation, three cases including RCM are set, as shown in Table 3. \( U_{w,lin} \) and \( H_{lim} \) are criteria for true wind speed (\( U_w \)) and significant wave height (\( H \)), respectively, which are determined to extract data deemed to be in a calm sea. \( U_{w,lin} \) is given as 7.9 m/s, corresponding to Beaufort scale 4. \( H_{lim} \) in meters is specified by eq. (13) considering the ship size.

\[
H_{lim} = 1.35 \frac{L_{pp}}{100}
\]

where \( L_{pp} \) is ship length between perpendiculars. \( H_{lim} \) of approximately 2.2 m and 1.8 m are given for PCS and MRT, respectively. In Case-1 and Case-2, the performance model expressed by eq. (10) and eq. (14) is applied to the voyages separately\(^8\).

\[
P = a_n \cdot \frac{N_E^{b_n} + c_n}{p}
\]

In contrast, in Case-3, the voyages are integrated into one voyage with the representative displacement in Table 2. Filtering to ensure a steady state is applied to Case-3, while the data with low engine revolution are eliminated for Case-2. Case-1 and Case-2 do not consider the corrections for displacement and winds and waves since the performance models were applied to the voyages separately and in each voyage the data in a state extremely close to a calm sea is extracted by filtering of true wind speed or both true wind speed and significant wave height. Case-3 requires correction for displacement by the Admiralty coefficient.
because voyages with varying displacements, as shown in Fig. 7, are integrated into one representative voyage. Correction for the effects of winds and waves is also required because the increase rate of resistance is necessary for the implementation of RCM.

Table 3 Cases for validation.

|                   | Case-1               | Case-2               | Case-3               |
|-------------------|----------------------|----------------------|----------------------|
| Performance model | Eq. (10) and eq. (14) | Eq. (10) and eq. (11) |                      |
| Integration of voyage data | Not accumulated | Accumulated |                      |
| Preprocessing (steady state) | None | Low \(\lambda_E\) eliminated | Preprocessed |
| Preprocessing (correction) | No correction | Preprocessed |                      |
| Filtering | \(U_w \leq U_{\text{win}}\) | \(U_w \leq U_{\text{win}}\), \(H \leq H_{\text{crit}}\) | RCM |

4.2 Voyage Simulation

The authors used the vessel performance simulator VESTA\(^9\) to conduct the voyage simulation for predicting performance in actual seas such as ship speed and fuel consumption. The features of VESTA include an accurate estimation of external forces due to winds and waves and a robust evaluation of performance considering engine characteristics. The effectiveness of VESTA was validated by comparison with onboard monitoring data for several merchant ships.

One of the inputs of the voyage simulation is performance in a calm sea. In this study, the performances evaluated in Case-1 to Case-3 were applied as the input, and voyage simulations were conducted for all the voyages listed in Table 2. Prior to the voyage simulation, the performance evaluated in Case-3 is corrected to that at the displacement in each voyage in accordance with the Admiralty coefficient. The specific fuel consumption curve obtained for each voyage is applied in the simulation for each voyage.

The results of the voyage simulation are compared with the onboard monitoring data in order to validate the effectiveness of RCM. Fig. 8 shows an example using the performance evaluated by RCM. Similar comparisons are conducted for all the voyages of PCS and MRT.

4.3 Results of Validation

The voyage simulation is conducted using the performance evaluated by Case-1 to Case-3 and compared with the onboard monitoring data. The comparisons between the voyage simulation and the onboard monitoring data result in Fig. 9 for PCS and Fig. 10 for MRT. For PCS, an improvement in the estimation of voyage distance is observed from Case-1 to Case-3, while the estimation of fuel consumption is similar in the three cases. For MRT, a clear improvement from Case-1 and Case-2 to Case-3 is observed in both the estimation of fuel consumption and the estimation of voyage distance.
For MRT, a clear improvement from Case-1 and Case-2 to Case-3 is observed in both the estimation of fuel consumption and the estimation of voyage distance. These results reveal that the performance curve derived from the developed evaluation method has sufficient accuracy for voyage simulations.

The authors calculated $\delta FOC$ and $\delta L_w$ among the three cases for all voyages, which are defined in eq. (15) and eq. (16), respectively, and summarized the results in Table 4. In the equations, $FOC$ and $L_w$ mean the cumulative fuel consumption and the voyage distance in one voyage, respectively. $L_w$ is equivalent to the integration of ship speed through water. The subscripts “sim” and “moni” denote voyage simulation and onboard monitoring, respectively.

$$\delta FOC = \frac{FOC_{sim} - FOC_{moni}}{FOC_{moni}}$$ (15)

$$\delta L_w = \frac{L_{w, sim} - L_{w, moni}}{L_{w, moni}}$$ (16)
The mean and standard deviation of $\delta_{\text{FOC}}$ and $\delta_{Lw}$ for PCS do not differ greatly among the cases. The voyage simulation provides a 3% overestimation of fuel consumption and a 1% underestimation of voyage distance.

For MRT, although providing a small $\delta_{\text{FOC}}$, Case-3 results in large standard deviation. Conversely, Case-2 results in a large $\delta_{\text{FOC}}$ with a small standard deviation. In Case-3, the smallest $\delta_{\text{FOC}}$ is obtained with a standard deviation similar to that of Case-2. It should be emphasized that the mean and standard deviation of $\delta_{Lw}$ decrease to zero in the order of Case-1, Case-2, Case-3. This means that stricter filtering for winds and waves can enable more accurate evaluation of the ship performance.

4.4 Discussion of Increase Rate of Resistance

The validation shows that the developed evaluation method is effective, especially for MRT, while all validation cases give similar results for PCS. In this section, the reason for the results is discussed in terms of the increase rate of resistance in actual seas.

While Case-3 includes correction for the effects of winds and waves, Case-1 and Case-2 do not consider this correction because the aim of these two cases is to extract data in a calm sea, and for such data, the influence of winds and waves on engine revolution and power is deemed to be negligible.

Case-2 specifies wind speed and significant wave height in order to extract data in a calm sea. Fig. 11 shows a probability density function (PDF) of the increase rate of resistance based on the data extracted in Case-2, and Table 5 summarizes its statistical analysis. Fig. 11 indicates that the peaks of the PDF for PCS and MRT-G1 are between 0% to 5% and that of MRT-G2 is between 5% to 10%, and the steepness of the peak for PCS is larger than that for MRT. The mean as a moment center is around 4.5% for PCS and 7.5% for MRT. This indicates that on the basis of the data after the filtering, winds and waves influence MRT more strongly than PCS.

The data with the increase rate exceeding 10%, which is shown in hatched area in Fig. 11, account for over 30% of all the data for MRT, while they account for only 15% for PCS. This implies that, even though filtering by a specific wind speed and significant wave height is applied to extract data for a calm sea, the extracted data can be influenced by winds and waves in terms of the increase rate of resistance.

The difference between the voyage simulation and the onboard monitoring data among the cases is remarkable for MRT and little difference is observed irrespective of filtering method for PCS. In other words, the filtering by only wind speed or both wind speed and significant wave height is also effective for PCS as well as the filtering by ASR. The authors are of the view that a key parameter for proper filtering is ship size because the increase rate of resistance of smaller ships is larger than that of larger ships under the same wind and wave condition, which is clarified in Table 5.

For further consideration, the results for MRT with Case-1 will be discussed in detail. Fig. 12 and Fig. 13 show the responses of $|\delta_{\text{FOC}}|$ and $|\delta_{Lw}|$, respectively, to the increase rate of resistance, based on the filtering of Case-1 indicated in Table 3. It is noted that, although the increase rate of resistance is not applied in Case-1, it is calculated for the data extracted by the filtering of Case-1 for this consideration. The abscissa in the figures denotes the mean of the increase rate in each voyage. The reason why we focused on the absolute value of $\delta_{\text{FOC}}$ and $\delta_{Lw}$ is that we intend to investigate the relationship between the severity of the sea state and the accuracy of the simulation by Case-1. From this viewpoint, it is not important whether $\delta_{\text{FOC}}$ and $\delta_{Lw}$ are positive or negative.

Fig. 12 and Fig. 13 demonstrate that $|\delta_{\text{FOC}}|$ and $|\delta_{Lw}|$ have a correlation with the mean of the increase rate of resistance in each voyage. The solid line in Fig. 12 is a linear approximation based on five data other than the datum at 10%. Fig. 12 shows that, except for the datum at 10%, the increase in $|\delta_{\text{FOC}}|$ is approximately linear with respect to the mean increase rate of resistance. This means that the voyage simulation with the ship performance in a calm sea obtained by filtering only by the wind speed of 7.9 m/s results in 5.2% error at least when evaluating the fuel oil consumption of MRT.
5. Conclusions

In this study, the authors addressed the validation of a developed evaluation method for ship performance in a calm sea which includes the Resistance Criteria Method (RCM), using the onboard monitoring data of a panamax container ship (PCS) and a medium range tanker (MRT) in service. RCM features filtering by the apparent slip ratio and filtering by the increase rate of resistance. The criteria for application of filtering by the apparent slip ratio, which results in an appropriate value considering the balance between the speed variation ratio and the number of data, were also discussed.

The validation was conducted by comparing the onboard monitoring data and the results of voyage simulations using the performance in a calm sea obtained by the developed evaluation method. This validation also includes voyage simulations using the performance derived from other methods, in which filtering by only wind speed or filtering by both wind speed and waves.

The results of the validation showed good agreement with the onboard monitoring data for both ships. The developed evaluation method was superior to other methods, especially for the MRT. This is attributed to the merits of the developed evaluation method in providing performance correction for the effects of waves and winds.

The effects of winds and waves on ship performance, specifically engine revolution and power, should be eliminated for an accurate evaluation of ship performance in a calm sea, but this cannot be achieved by limited filtering by a specified wind speed or significant wave height. This study clarifies the fact that the data extracted by limited filtering still include significant, non-negligible effects of winds and waves, especially in the case of smaller ships. In this respect, the evaluation method including RCM developed in this study is effective and can provide reliable evaluations for fine and blunt ships, although further validations are required using onboard monitoring data from other ships.

Acknowledgements

This study was performed as part of the Initiative on Evaluation of Ship Performance in Actual Seas, the “OCTARVIA Project,” a Japan Maritime Cluster Collaborative Research project. The authors are grateful to all the parties concerned who discussed the content of this study in the working groups.

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