Development of a Filtering Method for Evaluation of Performance in a Calm Sea Based on Onboard Monitoring Data

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Summary

Evaluations of ship performance in actual seas based on onboard monitoring data have been widely conducted recently. Performance in a calm sea is important for estimating performance in actual seas. In order to estimate performance in a calm sea, onboard monitoring data should be filtered by certain items and criteria. This filtering procedure is important and difficult because the data depend on the filtering items and criteria, and the appropriate items and criteria will be different depending on the ambient condition and ship size. To solve this problem, this paper proposes a filtering method called the Resistance Criteria Method (RCM) using the estimated added resistance in actual seas. The method was validated with a tanker (VLCC) and compared with other filtering methods.

Nomenclature

Abbreviations

- BF: Beaufort scale of wind
- ISO: International Organization for Standardization
- MCR: Maximum Continuous Output Rating
- RCM: Resistance Criteria Method
- VLCC: Very Large Crude oil Carrier

Greek symbols

- $\beta$: drift angle [deg.]
- $\delta$: rudder angle [deg.]
- $\nabla$: displacement [m$^3$]
- $\nabla_{rep}$: representative displacement [m$^3$]
- $\delta R$: rate of added resistance from calm sea [-]
- $\delta R_{eval}$: criterion of rate of added resistance from calm sea for “evaluation data” [-]
- $\delta R_{fit}$: criterion of rate of added resistance from calm sea for “fitting data” [-]
- $\nabla_r$: displacement of each voyage [m$^3$]
- $\Delta \nabla_r$: difference between ship speed through water by measurement and that on curve [knot]
- $\theta_w$: wave angle of wind waves [deg.]
- $\theta_s$: wave angle of swells [deg.]

Roman symbols

- $all$: all data
- $a_n$: coefficient of fitting curve [kW/rpm$^m$]
- $b_n$: coefficient of fitting curve

$C_{adin}$
Admiralty coefficient

$C_{EI}$
criterion for $EI$

$c_a$
coefficient of fitting curve [kW]

$C_1$
criteria for data calmer than BF5

$C_2$
criteria for data calmer than BF4

$d_{eval}$
evaluation data

$d_{fit}$
fitting data

$d_{ex}$
coefficient of fitting curve [rpm/knot]

$d_{norm}$
normal distance between data and power curve [-]

$EI$
evaluation index in RCM

$ex_1$
data after the filtering by criterion $C_1$

$ex_2$
data after the filtering by criterion $C_2$

$FIT$
fitting curve

$FIT_{ex1}$
fitting curve using the data $ex_1$

$FIT_{ex2}$
fitting curve using the data $ex_2$

$FIT_{1-5}$
fitting curve based on filtering method (No. 1 to No. 5, respectively)

$H_s$
significant wave height of swells [m]

$H_w$
significant wave height of wind waves [m]

$N$
number of evaluation data [-]

$N_E$
engine revolution [rpm]

$N_{Emcr}$
engine revolution at MCR [rpm]

$n_{id}$
corrected engine revolution [rpm]

$n_{ms}$
measured engine revolution [rpm]

$P$
engine power [kW]

$P_{emcr}$
engine power at MCR [kW]

$P_{id}$
corrected engine power [kW]

$P_{ms}$
measured engine power [kW]

$P_p$
propeller pitch [m]

$R_{id}$
resistance in still water [kN]

$R_{ms}$
total resistance in actual seas [kN]

$S_{a}$
apparent slip ratio [-]

$S_{a}$
sample mean of apparent slip ratio [-]
The proposed method is validated by comparison with other outlines the filtering method developed to solve those difficulties. Therefore this paper focuses on the method to estimate the ship performance in a calm sea based on onboard monitoring data. The purpose of this study is to investigate the appropriate filtering condition is different depending on ship size. Strict criteria narrow the number and range of the data obtained by a tank test. However the displacement or the trim is different depending on voyages. It is difficult to conduct tank tests of all displacement and trim that is possible to be in actual voyages in the future. The ship performance in a calm sea should be highly accurate. The ship performance in a calm sea can be obtained by a tank test. However the displacement or the trim is different depending on voyages. It is difficult to conduct tank tests of all displacement and trim that is possible to be in actual voyages in the future. Therefore this paper focuses on the method to estimate the ship performance in a calm sea based on onboard monitoring data.

The International Standards Organization (ISO) proposed one method for estimating ship performance in a calm sea by using onboard monitoring data in the standard relating to measurement of the performance change of hulls and propellers (ISO19030) \(^1\). However, this method is not sufficient for highly accurate estimation of performance in a calm sea because it does not consider wave effects.

Table 1 Principal particulars of Ship-A and Ship-B

| Ship ID | Ship-A | Ship-B |
|---------|--------|--------|
| Length between perpendiculars | 185.0 m | 270.0 m |
| Breadth | 32.2 m | 35.0 m |
| Design draft | 13.0 m | 12.0 m |

2. Difficulties of Filtering

2.1 Performance Model

In order to evaluate ship performance in actual seas, the relationship among the ship speed, engine revolution and engine power expressed by Eq. 1 and Eq. 2 identifies the ship performance in a calm sea\(^2\). \(V_c\) is the ship speed through water (knot), \(N_e\) is the engine revolution (rpm) and \(P\) is the engine power (kW). \(a_1\), \(b_1\), \(c_1\) and \(d_1\) are coefficients for the approximate curve. ISO 19030\(^1\) adopts Eq. 1 with \(c_1=0\).

\[
P = a_1 N_e^{b_1} + c_1
\]

\[
N_e = d_1 \cdot V_c
\]

2.2 Filtering Criteria

The performance model expressed by Eq. 1 and Eq. 2 is obtained by the least squares method using onboard monitoring data. The data should be filtered for two purposes: One is to ensure that data such as engine revolution and wind speed do not fluctuate in one sea condition because the calculation is assumed steady condition. This is “filtering for the steady state.” The other is to ensure that the data are not affected by ambient conditions, winds or waves. This is “filtering for external force.”

One of the difficulties of filtering is that the filtering criteria for external force cannot be determined by one value because the appropriate criteria are different depending on the affectation of the external force and data number. One example is shown below. The target ship is “Ship-A.” The principal particulars are shown in Table 1. “Ship-B” is mentioned in 3.6. The filtering criteria of external force are shown in Table 2. Here, \(C_1\) and \(C_2\) are criteria corresponding to the Beaufort scale of wind (hereinafter, BF) BF5\(^3\) and BF4, respectively. \(U_w\) is the true wind speed and \(H_w\) is the significant wave height. The data which have higher \(U_w\) and \(H_w\) than the criteria are eliminated. The data after filtering and the fitting curve are shown in Fig. 1. Here, \(all\) means all data. \(ex_1\) and \(ex_2\) are the data after the filtering by \(C_1\) and \(C_2\), respectively. \(FIT_{ex_1}\) and \(FIT_{ex_2}\) are the fitting curves using data \(ex_1\) and \(ex_2\), respectively. Fig. 1 shows that \(FIT_{ex_1}\) and \(FIT_{ex_2}\) are obviously different, which implies that the filtering criteria are important, but it is difficult to determine the appropriate criteria.

| Condition | \(U_w\) [m/s] | \(H_w\) [m] |
|-----------|---------------|-------------|
| \(C_1\) (BF5) | 9.8 | 2.0 |
| \(C_2\) (BF4) | 6.9 | 1.0 |
ship speed over ground.

Data when the engine revolution is smaller than the criterion are excluded to eliminate the effect of arriving at or leaving ports. Data with an absolute drift angle value larger than the criterion are excluded to eliminate the effect of drifting. Data with a rudder angle larger than the criterion are excluded to eliminate the effect of maneuvering. The absolute value of the difference between the ship speed through water and speed over ground larger than the criterion is excluded because the highly accurate ship speed through water should be used in the analysis.

| Item   | $N_E$ [knot] | $|\beta|$ [deg.] | $|\delta|$ [deg.] | $|V_v - V_g|$ [knot] |
|--------|--------------|-----------------|------------------|-----------------|
| Criteria | 40% $N_E$ MCR | 3.0             | 5.0              | 0.5             |

3. 2 Displacement Correction

Ship performance in a calm sea depends on displacement. The number of data obtained in one voyage is often small. In order to ensure an adequate number of data, the displacements close to a representative value are identified as one group. The ship performance of each displacement should be corrected to that of the representative displacement. The representative displacement is the average value during the analysis in this study.

The ship speed corrected by the Admiralty coefficient is expressed as Eq. 3. Here, $C_{adm}$ is the Admiralty coefficient and $V$ is the displacement. It is traditionally known that the Admiralty coefficient is almost the same when the change in displacement is small. Therefore, the corrected ship speed is obtained as Eq. 4 when the engine power is the same. Here, $V_{rep}$ is the ship speed of each displacement, $V_{rep}$ is the representative displacement and $V_{g}$ is the displacement of each voyage. The displacement is within ±3% of the representative displacement in this study.

$$C_{adm} = \frac{V^{3/2}V_v^{2/3}}{P}$$

$$V_{rep} = V_{rep} \left( \frac{V}{V_{rep}} \right)^{2/3}$$

3. 3 Correction for External Force

In order to improve accuracy, correction for the external force of winds and waves is carried out. The correction is based on Resistance –Thrust Identify Method. Added resistance in winds is estimated by the empirical formula and added resistance in waves is estimated by the theoretical method with simplified tank tests in short waves or empirical formula. The winds’ data measured onboard and the waves’ data provided by the Japan Weather Association (JWA) are used in this study. The measured engine revolution $n_{ms}$ and the measured engine power $P_{ms}$ are corrected to $n_{id}$ and $P_{id}$ at the same ship speed.

3. 4 Filtering by Apparent Slip Ratio

Even though filtering for the steady state is carried out, the
data are often scattered widely when the ship passes close to land and leaves and arrives at ports. To eliminate such data, the apparent slip ratio is introduced in filtering. The apparent slip ratio \( S_d \) is calculated by Eq. 5. Here, \( \bar{P}_p \) is the propeller pitch and \( \bar{n}_{el} \) is the corrected propeller revolution. The apparent slip ratio is normalized as Eq. 6. \( \bar{S}_d \) is the normalized apparent slip ratio and \( S_d \) is the sample mean of \( S_d \). The data sampling period is 1 hour.

\[
S_d = 1 - \frac{V}{\bar{P}_p \bar{n}_{el}} \quad (5)
\]

\[
\bar{S}_d = \frac{S_d - S_d}{S_d} \quad (6)
\]

The data which satisfy Eq. 7 is used for fitting. \( \sigma \) is the standard deviation of the normalized apparent slip ratio. This study applies \( C = 1.0 \). This value will be studied in detail by some ships and voyages in the OCTARVIA project.

\[
\left| \bar{S}_d \right| \leq C \cdot \sigma \quad (7)
\]

3. 5 Filtering by Increase Rate of Added Resistance

Filtering by the increase rate of added resistance is necessary even if the data are corrected because the corrected data include the error of weather measurements and forecasts and error due to the estimation of the hull form.

Conventionally, the filtering item for external force is the wave height or the wind speed. However, the appropriate criteria differ depending on the ship size.

Here, correction for external force has been conducted, which gives the rate of the resistance increase from a calm sea \( \Delta R \) obtained as Eq. 8. \( R_{ex} \) and \( R_{id} \) are estimated in the procedure of the correction for external force. \( R_{ex} \) is the total resistance in actual seas based on Resistance –Thrust Identify Method. \( R_{id} \) is derived from Eq. 9. \( \Delta R \) is the resistance increase due to winds and waves.

\[
\Delta R = \frac{R_{ex} - R_{id}}{R_{id}} \quad (8)
\]

\[
R_{id} = R_{ex} - \Delta R \quad (9)
\]

A smaller \( \Delta R \) can exclude data for low engine revolution because many low revolution data are corrected for comparatively severe weather conditions. However, since low engine revolution is important in severe weather, the criterion of \( \Delta R \) should be increased. In order to include the data of low engine revolution with high accuracy, the filtering procedure shown in Fig. 2 was developed. The filtering procedure is described as follows.

1) The data are filtered by the criterion of \( \Delta R \) to ensure they are extremely close to the calm sea condition. In the following, these data are called “evaluation data” and the criterion is expressed as \( \Delta R_{eval} \). For example, \( \Delta R_{eval} \) is 5%.

2) The data are filtered by the criterion of \( \bar{R} \), which is much larger than \( \Delta R_{eval} \) in order to ensure the low revolution data. These data are called “fitting data” and the criterion is expressed as \( \bar{R}_{fit} \). For example, \( \bar{R}_{fit} \) is 100%.

3) Using the fitting data, the fitting curve is obtained by the performance model.

4) Evaluation of the fitting curve by the “evaluation data” is necessary in order to decrease the affection of the error due to the correction of external force. The scattering level of the evaluation data around the fitting curve is calculated. If the result satisfies a certain level, the fitting curve is adopted. If the result does not satisfy that level, the criterion of the fitting data \( \Delta R_{fit} \) is changed to a smaller value with a certain resolution, for example, 1%, and procedures (2) to (4) are repeated based on the new \( \Delta R_{fit} \).

The fitting curve is evaluated with the evaluation index \( EI \) expressed as Eq. 10. The aims of \( EI \) are to evaluate the scattering level of the data not affected by the rate of the slope of the fitting curve, using the normal distance between the data and the curve. Here, \( N \) is the number of evaluation data, and \( d_{norm} \) is the normal distance between the data and the curve.

Each item is corrected as a non-dimensional value by using the designated ship speed \( (V_{dc}) \) for the ship speed, the maximum continuous revolution \( (N_{emc}) \) for the engine revolution and the maximum continuous output \( (P_{mcr}) \) for engine power. The outline of \( d_{norm} \) is shown in Fig. 3.

\[
EI = \sum_{i=1}^{N} \left( d_{norm}(i) \right)^2 \quad (10)
\]

![Fig. 2 Outline of filtering for external force](image-url)
3.6 Performance Model

The performance model is defined by the above Eq. 1 and Eq. 2. In those equations, the aim of $c_n$ is to improve the accuracy of fitting in the range of the data. The relationship between engine power and ship speed is expressed by Eq. 11 using Eq. 1 and Eq. 2. In terms of robustness, it is better that $c_n$ is 0, expressed as Eq. 12 and Eq. 13 instead of Eq. 1 and Eq. 11.

$$P = a_s d_s V_s^b + c_n$$  (11)
$$P = a_s N_s^b$$  (12)
$$P = a_s d_s V_s^b$$  (13)

In order to investigate the affection of $c_n$, the relationship between engine power and ship speed obtained from Eq. 11 and Eq. 13 is compared by the data of Ship-A and Ship-B. The principal particulars of these two ships are shown in Table 1 as mentioned in 2.2. Two displacement groups are obtained, respectively, as shown in Table 5. Right column is the representative displacement. $A_{des}$ is the design full load.

| Ship   | Group 1 | $80\% A_{des}$ | Group 2 | $51\% A_{des}$ |
|--------|---------|-----------------|---------|----------------|
| Ship-A | Group 1 | $80\% A_{des}$ | Group 2 | $51\% A_{des}$ |
| Ship-B | Group 1 | $93\% A_{des}$ | Group 2 | $102\% A_{des}$ |

Table 5 Displacement for voyage grouping

The data and fitting curves are shown from Fig. 4 to Fig. 7. $d_{fit}$ is the fitting data by $d_{fit}$ of $100\%$, $d_{eval}$ is the evaluation data by $d_{eval}$ of $2\%$, $FIT$ is the fitting curve with $c_n$ and $FIT_0$ is the fitting curve without $c_n$.

$FIT$ and $FIT_0$ overlap, the difference of engine power at the same ship speed is less than 1.5% and $EI$ is less than 0.1% in the range of $d_{fit}$ of all the displacement groups and ships. This means the difference of $FIT$ and $FIT_0$ is small. Therefore, in terms of robustness, the performance model is defined as Eq. 12 and Eq. 2 in the following.
3.7 Resistance Criteria Method (RCM)

The procedure of the proposed filtering method is explained below.

1) Filtering for steady state:
The engine revolution, drift angle, rudder angle and difference between the ship speed through water and speed over ground are considered.

2) Displacement correction:
To ensure the number of data, displacements with near values are treated as that of the same displacement and the ship speed of each displacement is corrected as that of the representative displacement based on the Admiralty coefficient.

3) Correction for external force:
Engine revolution and engine power are corrected to the calm sea at the same ship speed eliminated the effect of winds and waves.

4) Filtering by apparent slip ratio:
To exclude the data when the ship passes near land or arrives at or leaves ports, filtering by the apparent slip ratio is carried out.

5) Filtering by increase rate of added resistance:
Due to the added resistance from the calm sea, the ship size does not affect the result. To ensure the low revolution data with high accuracy, filtering is divided into two parts. One is based on the restricted criterion, and the other is based on the loose criterion. The two data are used for the evaluation of the fitting curve.

The above 1) to 3) has been conducted conventionally, and 4) and 5) are newly introduced in this paper. In order to distinguish the conventional filtering methods, the procedure 4) and 5) is called the “Resistance Criteria Method (RCM).”

The flowchart of the filtering procedure is shown in Fig. 8. Here, CEI is the criterion of EI.

4. Validation

The proposed filtering method is validated with Ship-C. The ship type is tanker (VLCC). The representative displacement is substantially equal to full load.

4.1 Data without Filtering by Apparent Slip Ratio

The result without the filtering of the apparent slip ratio is shown in Fig. 9. Filtering for the steady state, displacement correction, correction for external force and filtering by the increase rate of added resistance are conducted. $d_{fit}$ is the fitting data by $\delta R_{fit} = 100\%$, $d_{eval}$ is the evaluation data by $\delta R_{eval} = 5\%$ and FIT is the fitting curve. The circles shown by the solid line and broken line are the fitting data and the evaluation data, respectively, which are distant from the fitting curve.

To investigate the data in detail, the gap between the measured ship speed and the ship speed on the curve is expressed as $\Delta V_s$ and is calculated by Eq. 14. Here, $V_{ms}$ is the measured ship speed and $V_{curve}$ is the ship speed on the curve at the same engine revolution. The time history of the evaluation data of $\Delta V_s$ is shown in Fig. 10.

$$\Delta V_s = V_{curve} - V_{ms}$$ (14)

$\Delta V_s$ is large at the two points shown in Fig. 10, which are emphasized by the broken circles corresponding to the broken circles in Fig. 9. The gap is about 2 knots at both points. Here, let us examine the two points No. 238 and No. 373 in the broken circles in detail.
The time history of the wave hindcast data provided by the Japan Weather Association (JWA) is shown in Fig. 11. Here $H$, $T$ and $\theta$ are the significant wave height, mean wave period and wave angle, respectively. The subscripts $w$ and $s$ mean wind waves and swells, respectively. In the round brackets, eval means evaluation data, 238 means the data of No. 238 and 373 means the data of No. 373. 0° means heading waves. The added resistance due to waves from the right or left is the same, so the wave angle is not distinguished. These data are obtained from the grid point values of the weather hindcast by JWA. At No. 238 and No. 373, the significant wave height is 0 m to 2 m. The relative wave angle is distributed from following to beam. Therefore, the effect of the waves on the ship speed through water is expected to be small. Hence, it is necessary to investigate other reasons.

The ship positions at the two points are shown in the map in Fig. 12. Position of No. 238 is near Sri Lanka and position of No. 373 is in the Malacca Strait. Therefore, it is conceivable that the reason for the gap of the ship speed is not the affection of external force but the ship position near land or in the narrow strait. At such positions, it may be necessary to maneuver the ship or the ocean currents may be complex.

4.2 Data with Filtering by Apparent Slip Ratio

The result with filtering by the apparent slip ratio is shown in Fig. 13. The broken and solid circles are at the same locations as in Fig. 9. As shown in the graph, data which are off the fitting curve are excluded by the filtering of the apparent slip ratio. This indicates that filtering by the apparent slip ratio is effective for eliminating data in the unsteady state when the ship is near land or in a narrow passage.
4.3 Comparison of Various Filtering Methods

In order to validate the advantage of RCM, the fitting curves obtained by the various filtering methods shown in Table 6 are compared.

No. 1 assumes that correction for external force is not conducted and filtering is not conducted. No. 2 assumes that correction for external force is not conducted and filtering is conducted. No. 3 assumes that the data are corrected in terms of only winds and filtering is conducted. In particular, No. 3 basically follows the method described in ISO19030. No. 4 assumes that the data are corrected by winds and waves and filtering is conducted. No. 5 is the proposed filtering method. The data are corrected by winds and waves, and filtering for the steady state and RCM are carried out. In No. 5, the parameters $\delta_{Rfit}$ and $\delta_{Reval}$ are 100% and 5%, respectively. The criterion of $EI$, $CEI = 2.0$ and the number of the repetition is 1, in this case.

The fitting curves based on these filtering methods are shown in Fig. 14. FIT is the fitting curve, and the number of the subscript means the case number shown in Table 7. For reference, the evaluation data for case No. 5 are shown as $d_{eval}$. These evaluation data are corrected in terms of winds and waves and obtained by the strict filtering. Therefore, they are supposed to be nearest to the performance in a calm sea among the cases mentioned here.

The difference of the fitting curves is represented by $EI$. Here, the evaluation data of No. 5 shown in Fig. 14 are used in all the cases (No. 1 to No. 5). In Fig. 14, Engine power at the same ship speed by the method of No. 1 and No. 2 is obviously higher than the evaluation data because the correction and the filtering are inappropriate. The difference of fitting curve of No. 3 ~ No. 5 is small in Fig. 14.

| Case | Correction for external force | Filtering |
|------|-------------------------------|-----------|
| No. 1 | None                          | None      |
| No. 2 | None                          | Steady state (Table 3) and $\delta R$ not greater than 5% |
| No. 3 | Only winds                    | Wind speed not greater than 7.9 m/s and rudder angle not greater than 5° |
| No. 4 | Winds and waves               | Steady state (Table 3) and $\delta R$ not greater than 5% |
| No. 5 | Winds and waves               | Steady state (Table 3) and RCM (including apparent slip ratio) |

Fig. 15 Evaluation index (difference between evaluation data (No. 5) and each fitting curve) based on each method

Evaluation Index are shown in Fig. 15. In Fig. 15, $EI$ of No. 5 (RCM) is smaller than those of the other filtering methods. This shows RCM is effective as the filtering method.
5. Conclusions

A new filtering method was developed for highly accurate estimation of ship performance in a calm sea based on onboard monitoring data. The features of the proposed method are summarized below.

1) Filtering for the steady state.
2) Displacement correction based on the Admiralty coefficient.
3) Correction for external force in terms of winds and waves.
4) Filtering by the apparent slip ratio (RCM).
5) Filtering by the increase rate of added resistance (RCM).

The filtering method was validated with a tanker (VLCC). Some data that are off the curve are not eliminated without filtering by the apparent slip ratio. An investigation of the wave information and ship position revealed that the remaining data were not significantly affected by external force, but the ship was near land or in a narrow passage. Those data were eliminated by filtering by the apparent slip ratio. Therefore, this study confirmed the effectiveness of RCM including the filtering by the apparent slip ratio.

In order to compare RCM with other methods, several correction and filtering methods were set and compared using the evaluation index $E_I$. As a result, $E_I$ of RCM was smaller than those of the other filtering methods. This shows the effectiveness of RCM.

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