Decrease of Ship Speed in Actual Seas of a Bulk Carrier
In Full Load and Ballast Conditions

-Model Test and Onboard Measurement-

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Summary

Estimation of ship speed in actual seas is very important to evaluate the comprehensive performance in her life. Estimation of the added resistance in ballast condition is more difficult than that in full load condition due to the complicated phenomena around the bulbous bow. The proposed method, which combines tank tests with calculation, shows the estimation of added resistance in ballast condition accurate for a Panamax bulk carrier.

In this paper, the proposed method is applied to a handy-size bulk carrier (approximately 160m length) equipped with cranes in both ballast and full load conditions, and its accuracy is confirmed by model tests and onboard measurements. Moreover the difference of resistance components due to winds and waves is discussed in terms of load condition toward the improvement of evaluation of performance in actual seas for handy-size bulk carriers equipped with cranes.

1. Introduction

In order to reduce Greenhouse Gas (GHG) from shipping sector, development of new technology is required for vessels with more efficient fuel consumption. Improving accuracy of estimation on ship performance in actual seas helps ship builder to design more energy efficient ships. Considering efficient and safe ship’s operation, one of the key factors is accurate calculation of decrease of ship speed due to winds and waves.

Theory of added resistance due to waves in terms of wave field around a ship has been derived by Maruo1). In a practical viewpoint, the assumption of slender body theory used in the calculation shows the difference between calculation and tank test result. This discrepancy is mainly observed in short waves, so that the correction of diffraction force is needed. Firstly, Fujii and Takahashi2) proposed a semi-empirical formula that is expressed as a function of separation of variables; hull form, wave frequency and ship speed. The functional expression of ship speed is derived from experiments for blunt ships. Recently, a practical correction method is proposed by Tsujimoto et al.3). The method keeps practical accuracy by using the tank test results and shows good agreement with tank test results and onboard measurement data by some kinds of ships in full load condition4,5).

Considering ship’s operation for blunt ships, estimation of ship performance in ballast condition has large impact to evaluation of performance along the operational profile. Estimation of added resistance in ballast condition, however, is more difficult than that in full load condition since the wave making and breaking phenomena around bulbous bow exist. Meanwhile, since the proposed method takes account of these phenomena by using tank test results in short waves, it is fundamentally capable of capturing these phenomena and influence of bow shape above water as well. Ichinose et al.6) has applied the method for a Panamax bulk carrier in ballast condition and confirmed the effectiveness. The study shows good agreement with tank test results.

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Fig.1 Object bulk carrier.

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This paper presents an example of the application of the proposed method to the handy-size bulk carrier (approximately 160m length) equipped with 4 cranes shown in Fig.1 and confirmed the effectiveness of the method by model tests and onboard measurements. Moreover, the difference of resistance components due to winds and waves between full load and ballast conditions is discussed in order to improve the evaluation method of ship performance in actual seas for handy-size bulk carriers equipped with cranes.

2. Calculation Method

Decrease of ship speed in a weather condition \( \Delta V \) is evaluated at constant power and defined by equation (1).

\[
\Delta V = V_{ref} - V_w
\]  

where; \( V_{ref} \) is ship speed in a calm sea condition and \( V_w \) is ship speed in a weather condition. The image of the procedure to obtain \( \Delta V \) is shown in Fig.2.

In actual seas, natural forces such as winds and waves are acting on a ship in addition to the resistance in a calm sea condition. These forces are separated into 4 dominant components (wave force, wind force, forces due to drift and steering). Decrease of ship speed is obtained by solving equilibrium equations under the condition where engine output is constant.

Among these forces, added resistance due to waves has generally larger impact in severe weather conditions. Therefore the estimation of added resistance due to waves requires particular attention to the accuracy.

2.1 Added resistance in waves

2.1.1 Added resistance in short crested irregular waves

A dded resistance in short crested irregular waves \( R_{AW} \) is calculated by linear superposition of added resistance in regular waves \( R_{AR} \) and is expressed by equation (2).

\[
R_{AW}(V, H, T, \theta, \omega, \alpha) = 2 \int \frac{R_{AR}(V, \omega, \alpha)}{\zeta} \cdot E(\omega, \alpha; H, T, \theta) \, d\omega \, d\alpha \tag{2}
\]

where; \( V \); ship speed, \( H \); significant wave height, \( T \); mean wave period, \( \theta \); primary wave direction, \( \omega \); circular frequency of incident regular waves, \( \alpha \); encounter angle between ship and regular waves (angle 0 deg. is defined as the heading direction), \( \zeta \); amplitude of regular waves and \( E(\omega, \alpha; H, T, \theta) \); the directional spectrum prescribed in IACS Rec. No.34\textsuperscript{th}.

2.1.2 Added resistance in regular waves

A dded resistance in regular waves \( R_{AR} \) is composed of added resistance primary induced by ship motion \( R_{AR}^M \) and that due to wave reflection \( R_{AR}^R \), which is expressed as equation (3).

\[
R_{AR}(V, \omega, \alpha) = R_{AR}^M(V, \omega, \alpha) + R_{AR}^R(V, \omega, \alpha) \tag{3}
\]

In the equation, \( R_{AR}^M \) is calculated by M aruo’s theorem using Kochin function obtained by assumption of slender body theory, and \( R_{AR}^R \) is a correction for diffraction force and expressed in equation (4).

\[
R_{AR}^R(V, \omega, \alpha) = \frac{1}{2} \rho g \frac{L}{V^2} B \frac{\alpha}{2} \left( 1 + K \right) \tag{4}
\]

where; \( \rho \); fluid density, \( g \); gravitational acceleration, and \( B \); ship breadth.

The equation comprises the bluntness coefficient \( K \) defined by equation (5), effect of draft and encounter frequency \( \alpha \) and effect of advance speed \( 1 + \alpha \).

\[
K(\alpha) = \frac{1}{B} \left\{ \frac{\sin^2(\alpha + \beta_{\alpha}) \sin \beta_{\alpha} \, d\alpha}{I_{I}^{} \beta_{\alpha} \sin \beta_{\alpha} \, d\alpha} + \frac{\sin^2(\alpha - \beta_{\alpha}) \sin \beta_{\alpha} \, d\alpha}{I_{II}^{} \beta_{\alpha} \sin \beta_{\alpha} \, d\alpha} \right\} \tag{5}
\]

where; \( I_{I}, I_{II} \); domains of integration as shown in Fig.3, \( \beta_{\alpha} \); slope of line element along the water line, and \( d\alpha \); line element along the water plane.
where; \( I_1 \): modified Bessel function of the first kind of order 1, 
\( K_1 \): modified Bessel function of the second kind of order 1, 
\( k \): 
wave number of regular waves and \( d \); draft. Note that as for ships with trim, Ichinose et al. \(^6\) reported that application of the deepest draft \((d_a)\) to the representative draft gives good agreement with calculation and the tank tests of added resistance in regular waves.

Effect of advanced speed \( (\alpha_0) \) is approximately expressed as a linear function of Froude number \((F_a)\) in the speed range of ocean going. The formula is expressed as equation (9), \(^3\), \(^6\)

\[
a_0(V, \alpha) = C_a(\alpha) \cdot F_a
\]

Coefficient of advanced speed in heading waves \( (C_a(\alpha = 0)) \) is determined by tank tests with different ship speed in short waves of a single wave length and calculated by equation (10).

\[
C_a(\alpha = 0) = \left( \frac{R_{aw}^{Exp} - R_{aw}^{Form}}{0.5 \rho_g \frac{\pi}{2} B H} \right) \left( \frac{1}{F_a} \right)
\]

where; \( R_{aw}^{Exp} \); measured added resistance in regular waves.

2.2 Wind resistance and other hydrodynamic forces

Wind resistance \( (R_a) \) is calculated by equation (11). The coefficient of longitudinal wind force \( (C_{awind}) \) is estimated by the formula of Fujiwara et al. \(^9\), which is based on model tests in a wind tunnel.

\[
R_a(V_w, \gamma_w) = \frac{1}{2} \rho_w A_T V_w^2 C_{awind}
\]

where; \( \rho_w \); air density, \( A_T \); front projected area above water line, \( V_w \); relative wind speed and \( \gamma_w \); relative wind direction. Lateral wind force \((V_x)\) and yaw wind moment \((N_y)\) is calculated as well.

Resistance, lateral force and yaw moment due to drift motion \( (R_d, V_x, N_y) \) is calculated by the regression formulas \(^10\), \(^11\) based on the tank tests and composed by hull form parameters.

Resistance, lateral force and yaw moment due to steering \( (R_s, V_x, N_y) \) is calculated by the regression formulas based on the tank tests \(^10\), \(^11\).

2.3 Equilibrium equations

Ship speed in actual seas is obtained by solving equilibrium equations in steady navigating condition on the fixed course. The coordinate system is shown in Fig.4.

\[
X \cos \beta + Y \sin \beta = 0
\]

\[
X \sin \beta - Y \cos \beta = 0
\]

\[
N = 0
\]

\[
X = (1 - \tau) X_p - R_i
\]

\[
Y = Y_p(\beta) + Y_a(\beta, \delta) + Y_d(V_x, \gamma_w)
\]

\[
N = N_p(\beta) + N_a(\beta, \delta) + N_d(V_x, \gamma_w)
\]

\[
R_i = R_{th} + R_s + R_{aw} + R_0 + R_k
\]

where; \( X_p \); propeller thrust, \((1 - \tau) \); thrust deduction coefficient, \( R_{aw} \); resistance in still water.

Since characteristics of self-propulsion factors and propeller open water in a weather condition, not rough weather condition, do not have much difference from those in a calm sea condition \(^14\), \(^15\), both characteristics in a calm sea condition are used for the estimation of delivered power.

3. Model tests

The calculation method is applied to the bulk carrier whose principal particulars are shown in Table 1. Model tests at the towing tanks are carried out to determine the coefficient of advanced speed in heading waves \( (C_a(\alpha = 0)) \).

3.1 Model test in the towing tanks

Two scaled model ships (one is approximately 6.0m and
another is 4.4m length) were tested at Mitaka No.2 model basin (length: 400m, width: 18m, depth: 8m with wave generators of plunger type) for 6.0m length model ship and actual sea model basin (length: 80m, width: 40m, depth: 4.5m with wave generators around the entire periphery) for 4.4m length model in National Maritime Research Institute (NMRI), Japan. Situation of the resistance test in waves is shown in Fig.5. The test in ballast condition was conducted only by 6.0m length model.

Table 1 Principal particulars in two conditions.

<table>
<thead>
<tr>
<th>Load condition</th>
<th>Full</th>
<th>Ballast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length between perpendiculars (L) [m]</td>
<td>160.40</td>
<td>10.60</td>
</tr>
<tr>
<td>Breadth (B) [m]</td>
<td>27.20</td>
<td>10.80</td>
</tr>
<tr>
<td>Fore Draft (d_f) [m]</td>
<td>9.70</td>
<td>4.20</td>
</tr>
<tr>
<td>Aft Draft (d_a) [m]</td>
<td>9.70</td>
<td>5.95</td>
</tr>
</tbody>
</table>

3.1.1 Coefficient of advanced speed in heading waves

To determine the coefficient $C_\alpha$, resistance tests in regular heading waves of short wave length are performed. The effect of advanced speed ($\alpha$) under each conditions in heading waves, whose wave length - ship length ratio is 0.3 ($\lambda/L = 0.3$), is shown in Figs.6 and 7. Here, the coefficient $C_\alpha$ in full load condition were obtained as 10.6 at Mitaka No.2 model basin and 10.8 at actual sea model basin respectively. This confirms the robustness of proposed method. The coefficient $C_\alpha$ in ballast condition was obtained as 13.0 at Mitaka No.2 model basin.

3.1.2 Frequency responses of added resistances in heading waves

Frequency response functions of added resistance in heading waves of full load and ballast conditions were calculated using the experimentally-obtained coefficient $C_\alpha$. Fig.8 shows the results of calculation, where: $K_{aw}$ is non-dimensional added resistance defined as equation (19).

$$K_{aw} = \frac{R_{aw}}{4 \rho \bar{u}^2 L}$$ (19)

The result of the calculation shows good agreement with that of the tank tests in full load condition. Furthermore, the figure indicates that wave length at peak in ballast condition is shorter than that in full load condition.

3.2 Model test in wind tunnel

To investigate the resistance due to wind force, the model tests (scale 1/100) were carried out at the wind tunnel (length of test section 15m, width 3m, height 2m, maximum wind velocity 30m/s) in NMRI. The model ship at the tunnel is shown in Fig.9. The experimental results and the calculation results by the formula of Fujiwara et al. are shown in Fig.10. $C_{aw}$ is normalized coefficient of longitudinal wind force defined as equation (20).
where; $C_{\text{wind}}^{\text{exp}}(\gamma_r = 0)$; the experimental-obtained coefficient at heading wind direction $\gamma_r = 0$ (different in each loading condition).

The difference of the coefficients of longitudinal wind force ($C_{\text{wind}}$) between full load and ballast condition was 0.6% at heading winds. This means that resistance due to wind is approximately proportional to front projected area above water line ($A_p$) for this ship, where the 26.7% increase of $A_p$ results in the 27.5% increase of resistance due to wind.

The difference of $C_{\text{wind}}$ between the calculation and the model tests affects the difference in the estimation of decrease of ship speed. The difference in Beaufort 6 of heading weather is 0.14 knot in full load condition and 0.31 knot in ballast condition, respectively.

According to the wind tunnel tests of another handy-size bulk carrier without cranes, the test result tends to be closer to estimation by the Fujiwara’s formula so that cranes on board of the vessel may affect to increase the coefficient $C_{\text{wind}}$. Research for the effect of cranes is expected future.

4. Onboard measurement

To confirm the effectiveness of the proposed calculation method and to compare the difference in decrease of ship speed by different load condition, onboard measurements of the object ship have been performed. Representative measured items and equipment are shown in Table 2. The system conducts a measurement for 30 minutes every hour and records statistical data automatically. Sampling frequency is set to be 1 Hz. As for wave measurement, the system analyses the images obtained by X band radar for 2 minutes half-hourly. The accuracy of this wave measurement system is validated by Kuroda et al. 16). The anemometer is located at a height of 29 m above water line in full load condition and it is installed on radar mast on the bridge. Measured wind data is directly used for the analysis.

4.1 Measurement data

Shipping area of the object ship is East Asia, North America and Australia. The measurements were carried out in about 14 months from December 2009 when it entered into service to February 2011.

<table>
<thead>
<tr>
<th>Item</th>
<th>Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>GPS</td>
</tr>
<tr>
<td>Ship position</td>
<td>Ship speed over ground</td>
</tr>
<tr>
<td>Ship speed through water</td>
<td>Doppler log</td>
</tr>
<tr>
<td>Course</td>
<td>Gyro compass</td>
</tr>
<tr>
<td>Rudder angle</td>
<td>Rudder angle indicator</td>
</tr>
<tr>
<td>Shaft power</td>
<td>Shaft power indicator</td>
</tr>
<tr>
<td>Propeller revolution</td>
<td>Revolution indicator</td>
</tr>
<tr>
<td>Relative wind speed</td>
<td>Anemometer</td>
</tr>
<tr>
<td>Relative wind direction</td>
<td></td>
</tr>
<tr>
<td>Significant wave height</td>
<td>Radar wave measurement</td>
</tr>
<tr>
<td>Wave direction</td>
<td></td>
</tr>
<tr>
<td>Displacement</td>
<td>Voyage record</td>
</tr>
<tr>
<td>Draft</td>
<td></td>
</tr>
</tbody>
</table>

4.2 Data screening

The effective data, defined as all item in Table 3, were picked up. Then 3046 data in full load condition and 1318 data in ballast condition were obtained. To keep the accuracy of ship speed measurement, these data were screened under the condition of speed difference within 0.5 knot between ship speed through water and that over ground. In addition, since constant engine output is assumed in ship performance evaluation, data within 75% MCR ±5% were screened.

In these screened data, 8 data (under full load condition) and 30 data (under ballast condition) were picked up as the data in heading weather conditions defined as direction of waves and winds is within ±22.5°. The decrease of ship speed of the raw data is shown in the upper left figures of Figs. 11 and 12 under full
load and ballast condition respectively. The reference speed \( V_{ref} \) is determined by analyzing measured data which are assumed to be in a calm sea. Solid lines in these figures indicate the calculation result using the test results in wind tunnel. Whereas, the plotted points in these figures are measured in different conditions in terms of displacements, power outputs and weather conditions.

### Table 3 Items for analysis.

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship speed over ground</td>
<td>knot</td>
</tr>
<tr>
<td>Ship speed through water</td>
<td>knot</td>
</tr>
<tr>
<td>True wind speed</td>
<td>m/s</td>
</tr>
<tr>
<td>True wind direction</td>
<td>deg.</td>
</tr>
<tr>
<td>Significant wave height</td>
<td>m</td>
</tr>
<tr>
<td>Wave direction</td>
<td>deg.</td>
</tr>
<tr>
<td>Shaft power</td>
<td>kW</td>
</tr>
<tr>
<td>Displacement</td>
<td>ton</td>
</tr>
</tbody>
</table>

#### 4.2.1 Data correction for displacement and shaft power

Since data of displacement and shaft power in operation are not constant, data correction for displacement and shaft power enables these data more useful for evaluation of ship performance. So in this study, designated shaft power and displacements were defined as 75% MCR and 100% load displacement for full load condition and approximately 50% load displacement for ballast condition, respectively. The correction of ship speed is based on the idea that admiralty coefficient \( C_{adm} \) is constant.

\[
C_{adm} = V^3 \cdot \frac{P}{P'}
\]  

(21)

where; \( V \); ship speed, \( P' \); displacement and \( P \); shaft power.

The corrected decrease of ship speed in the data is shown in the upper right figures of Figs.11 and 12 under full load and ballast condition respectively.

#### 4.2.2 Data Correction for weather condition

Though ships encounter various weather conditions, designated weather condition enables us to easily understand of her performance. In this study, the Beaufort scale, one of the most popular indexes of weather conditions, is used for analysis. Weather conditions that the object ship encountered are shown in Fig.13. The line in the figure is linear-interpolated value of the Beaufort scale.

Decrease of ship speed due to winds used for correction of measured ship speed through water was estimated by the experimental results in wind tunnel. The corrected decrease of
Decrease of Ship Speed in Actual Seas of a Bulk Carrier in Full Load and Ballast Conditions

ship speed in terms of significant wave height is shown in the
lower figures of Figs.11 and 12.

Figs.11 and 12 show that the present calculation results have
good agreement with onboard measurement results, and it
supports the fact that the ship performance in actual seas is
estimated by the present calculation method in both full load and
ballast conditions with practical accuracy. In addition, Figs. 14
and 15 show decrease of ship speed in terms of true wind speed.
Solid lines show calculation results by test results in wind tunnel
and dotted lines indicate calculation results using the Fujiwara’s
formula for reference. These figures show similar tendency to
Figs.11 and 12.

5. Resistance components comparison
in full load and ballast conditions

As previously discussed, it becomes clear that the present
method enables us to estimate ship performance in actual seas of
this bulk carrier with practical accuracy. Thus, this method allows
us to compare resistance components in full load and ballast
conditions. Figs.16 and 17 show resistance components in
Beaufort 5 (H = 2.0m, V_{wind} (True wind speed) = 9.8m/s) and
Beaufort 6 (H = 3.0m, V_{wind} = 12.6m/s), respectively. Where;
added resistance due to winds is estimated by test results and
includes effect of air resistance due to the ship running of 15knot.

Fig.16 indicates that in Beaufort 5, added resistances due to
waves (RAW) of each conditions are 15% of full load condition in
a calm sea and 16% of ballast condition in a calm sea,
respectively, and that due to winds (RA) are 16% in full load
condition and 23% in ballast condition. Among these components,
added resistance due to winds under ballast condition is
comparatively larger than the others.

In Beaufort 6, added resistance due to waves stands out and
reaches about half of resistance in a calm sea, and it is 41% in full
load condition and 44 % in ballast condition.

Fig.14 Decrease of ship speed under full load condition in
heading winds and waves. (Upper left : raw data,
Upper right : data corrected by displacement and
power, Lower : data corrected by wave condition)

Fig.15 Decrease of ship speed under ballast condition in
heading winds and waves. (Upper left : raw data, Upper
right : data corrected by displacement and power,
Lower : data corrected by wave condition)
6. Conclusions

In this paper, the proposed method for the estimation of decrease of ship speed in actual seas of a handy-size bulk carrier (approximately 160m length) equipped with cranes is applied with the aim of evaluating the influence of loaded conditions on the vessel's performance in actual seas. As a result, the following conclusions are derived.

1) The present calculation method is capable of estimating decrease of ship speed both in full load and ballast conditions with practical accuracy.

2) Added resistance due to winds in Beaufort 5 under ballast condition at 15 knot is 23% of resistance in a calm sea and comparatively larger than added resistance due to waves.

3) In Beaufort 6, added resistances due to waves reach about half of resistance in a calm sea.

In this paper, bulk carriers without cranes are not investigated. The consideration of effect of cranes on added resistance due to winds is expected in the future.

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References


