Investigation on Trim Optimization to Enhance the Propulsive Performance of Fine Ships

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Summary

In order to reduce greenhouse gas (GHG) from shipping sector, it is necessary not only to build eco-friendly ships but also make some efforts for reduction of GHG from ships in service. In this regard, especially for fine ships such as a vehicle carrier and a container ship, it is well known that ship propulsive performance can be enhanced by trim optimization, which can contribute to environmental protection and can bring ship operator economic benefit due to fuel saving.

This study addresses trim optimization for propulsive performance by the means of model tests. Model tests are conducted for various trim conditions and the required power is estimated for consideration of trim effect in still water. The effect of draft and trim variation on propulsive performance is investigated and the trim condition in which required power can be saved is clarified.

1. Introduction

At January 2013, International Maritime Organization (IMO) has got into force Energy Efficient Design Index (EEDI) regulation with which ships engaging in international voyage shall comply. Further, Ship Energy Efficient Management Plan (SEEMP) has been made mandatory to be provided on board for reduction of greenhouse gas (GHG) from ships in service. These require not only shipyard to build high-performance ship but also ship operators to operate ships with low emission of GHG. For example of the latter, slow steaming or weather routing is deemed effective for fuel saving and actually put into practice.

Trim optimization is expected as a means for enhancing energy efficiency in service. While ships are generally optimize-designed at one design speed for one design full-load condition, in actual service draft condition varies widely depending on the amount of cargo, which means that the ships are mostly operated out of optimized design condition. In addition, recently majority of ships engaging in international voyage is operated by means of slow steaming. These facts imply that optimized trim does exist for various draft conditions and that there is potential for fuel saving by trim optimization.

Yazaki et al. 1) has carried out model test in order to clarify relations between resistance and trim at ballast condition of tanker. Yanagihara and Kawakami 2) has tested bulk carrier models for investigation on the effect of loading condition on the propulsive performance. The latter addressed not only resistance but also self-propulsion performance and discussed the trim effect on self-propulsion factor in detail.

Tsugane et al. 3) investigated the potential of fuel saving through model tests and full-scale measurements and concluded that in some cases trim by head can save fuel oil consumption. Larsen et al. 4) conducted model test with trim variation for one specified draft and investigated trim effect on resistance coefficient and self-propulsion factor and reached similar conclusion to Tsugane et al. Several studies 5)6)7)8)9)10) has conducted both model test and computational fluid dynamics (CFD) in order to clarify trim effect on resistance.

Most of the previous studies focus on trim optimization at specified draft condition. As ships in service vary its draft widely, the relationship between draft and optimized trim should be clarified. This study investigates on trim optimization for propulsive performance of fine ships such as a vehicle carrier and a container ship based on model tests in which both draft and trim condition is varied. The effect of trim variation on propulsive performance is clarified and potential of fuel saving by trim variation is investigated.

2. Model Test

Principal particulars of a vehicle carrier and a container ship used in this study are shown in Table 1 and Table 2, respectively. Draft and trim condition of the objected ships is determined as shown in Table 3, based on draft records of ships in service whose particulars are deemed equivalent, taking into account that the propeller does not emerge into air. Profile of fore part is shown in Fig. 1 and Fig. 2.

2.1 Reliability of Model Test

This study discusses trim effect on each component required for power estimation based on the results obtained in model tests. This means that sufficient accuracy of model test is required for evaluation of trim effect on propulsive performance. To clarify model test accuracy, author et al. 11) has conducted multiple resistance test and carried out uncertainty analysis, by using the same model ship as used in this study. Uncertainty of resistance coefficient is assessed to be 2.1%, which has ensured that resistance test accuracy is reliable. Further, author et al. has carried out multiple self-propulsion test and ensured its repeatability and reproducibility although uncertainty analysis for propulsion-factors has not been carried out.
2.2 Resistance Test

Resistance test is carried out for the vehicle carrier and the container ship. Ship speed is set to ship speed 8.0 knot to 22.0 knot in Full-scale for the vehicle carrier, and 11.0 knot to 28.0 knot in Full-scale for the container ship. Prohaska Method is applied for obtaining form factor $K$ with frictional resistance coefficient of a corresponding plate based on Schoenher’s Formula. Form factor and wave making resistance ($C_w$) defined in Eq. (1) of the vehicle carrier and the container ship is shown in Fig. 3 to Fig. 6, respectively. Froude number is defined as Eq. (2).

\[ C_s = \frac{R_w}{\frac{1}{2} \rho S_w V_s^2} \]
\[ F_s = \frac{V_s}{\sqrt{gL_{wl}}} \]

where $R_w$ is dimensional wave making resistance, $\rho$ is fluid density, $S_w$ is wetted surface area, $V_s$ is ship speed, $g$ is acceleration of gravity, $L_{wl}$ is length on waterline. $S_w$ and $L_{wl}$ are varied by draft and trim.

Both for the vehicle carrier and the container ship, form factor decreases in proportion to increase of draft. With respect to trim effect on form factor, different tendency can be observed between the two ships.

For the vehicle carrier form factor is almost decreasing when trim by stern is getting larger, which is remarkable in shallow draft condition. On the other hand, the effect of trim of container ship on form factor is seemed negligible. In this case, form factor of the container ship can be regarded as constant with respect to trim variation.

Reichel et al. 12) indicated that for container ship form factor increased slightly with trim due to increasing submerged aft part, which differs from the results shown in Fig. 4. This may result from difference of form of subjected container ship, especially aft part.
Form factor of ship having no trim can be considered as minimum among those of ship with varying trim for specified drafts. Generally, in spite of trim by head or by stern, trim brings increase of viscos pressure resistance since the extent of separation of flow around ship with trim gets stronger than that around ship with no trim. In this case, trim effect on form factor appears for the vehicle carrier in shallow draft condition.

The same trim effect on wave making resistance can be observed between the two ships. For shallow draft condition, especially at low speeds, trim by head gives less wave making resistance because the bulbous bow can be kept appropriately submerged. Trim by stern in shallow condition encompasses emersion of the bulbous bow into the air, which leads to increase of wave making resistance.

In deep draft condition, trim by head increases wave making resistance because the bulbous bow is kept excessive depth and
cannot work effectively for reduction of wave making resistance. Therefore, from the viewpoint of wave making resistance in deep condition, no trim is considered as optimized condition.

2.3 Self-Propulsion Test

Self-propulsion test is conducted for the vehicle carrier. Principal particulars of a model propeller used in the test is as Table 4. The model propeller is equipped with trip wires as turbulence stimulator. Self-propulsion factors are obtained by thrust identified method. While propeller depth varies depending on draft and trim condition in the self-propulsion test, propeller open characteristics measured with its depth sufficiently submerged is utilized.

Table 4 Principal particulars of a model propeller for vehicle carrier.

<table>
<thead>
<tr>
<th>item</th>
<th>Model</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>0.15</td>
<td>[m]</td>
</tr>
<tr>
<td>Pitch ratio</td>
<td>1.1</td>
<td>[-]</td>
</tr>
<tr>
<td>Expanded area ratio</td>
<td>0.7</td>
<td>[-]</td>
</tr>
</tbody>
</table>

Thrust deduction coefficient (1-η), effective wake coefficient (1-wM), and relative rotative efficiency (η) is shown in Fig. 7 to Fig. 9, respectively. These results are average value with respect to ship speed while self-propulsion test is carried out with Froude number 0.215 to 0.250 corresponding to ship speed 18.0 knot to 21.0 knot in Full-scale.

Regardless of mid draft, thrust deduction coefficient and relative rotative efficiency are constant and not influenced by trim variation. Regarding effective wake coefficient, two clear tendency can be observed from Fig. 8. One is that effective wake coefficient increases as trim by stern increases, and another is that shallower draft gives smaller effective wake coefficient. These tendencies imply that effective wake coefficient depends on aft draft (dA).

Relation between aft draft and effective wake coefficient is shown in Fig. 10, which indicates that effective wake coefficient tends to increase in proportion to increase of draft at AP. It is speculated that viscos flow including boundary layer around aft part deteriorates as draft at AP increases.

Prediction of the effective wake coefficient would be helpful in estimating energy saving by trim variation. Although Fig. 10 shows good correlation between draft at AP and effective wake coefficient, other parameters having better correlation are sought for more accurate estimation, which gives Eq. (3).

$$1 - w_M = C_0 + C_1 \left( \frac{L_{pp}}{B} \right) \left( \frac{B}{d_a} \right)$$

In this case, $C_0$ and $C_1$ are respectively 0.4964 and 5.2571. Correlation factor with the effective wake coefficient given by Eq. (3) is 0.9827, which gives better fitting than that shown in Fig. 10. Since $C_0$ and $C_1$ can be obtained through propulsion test for minimum draft and trim condition, draft and trim effect on effective wake coefficient can be comprehended without draft and trim variation.

3. Power Estimation

Based on the results of model test, brake power in watt (BHP) is estimated for the vehicle carrier. Resistance in full-scale is estimated according to Hughes Method. With effective power in watt (EHP) and propulsive efficiency ($\eta$), brake power is calculated by Eq. (4).

$$BHP = \frac{EHP}{\eta} = \frac{0.5 \rho V^3_s S}{1} \left\{ \frac{1}{1 - \Delta C_f} + C_{wS} + \Delta C_{wM} \right\} \left( 1 - \frac{1}{1 - w_M} \right) \cdot \eta_r \cdot \eta_h \cdot \eta_o$$

where $C_{wS}$ is frictional resistance coefficient of a corresponding plate, $\Delta C_f$ is roughness allowance, 1-$w_M$ is effective wake coefficient for full-scale ship, $\eta_r$ is open water propeller efficiency, and $\eta_o$ is transmit efficiency.

$\Delta C_f$ is estimated by standard equation of Japan Ship research Center [13]. 1-$w_M$ is estimated with full-scale correction by Yazaki’s formula [14].

For all draft and trim condition shown in Table 3, effective power, propulsive efficiency, and brake power are estimated. In order to investigate trim effect on these, the rate of change is defined as shown in Eq. (5) to Eq. (7). Rate of change for effective power, propulsive efficiency, and brake power is shown in Fig. 11 to Fig. 13, respectively.

$$\delta EHP = \left( \frac{EHP_{w/trim}}{EHP_{w/trim}} - 1 \right) \times 100$$

$$\delta \eta = \left( \frac{\eta_{w/trim}}{\eta_{w/trim}} - 1 \right) \times 100$$

$$\delta BHP = \left( \frac{BHP_{w/trim}}{BHP_{w/trim}} - 1 \right) \times 100$$

Effective power of ship with trim by head is smaller than that with trim by stern for overall speed and draft. While trim by head can reduce effective power for draft 7.6 m, it rarely contributes to power reduction for draft 8.3 m and 9.0 m. For draft 9.0 m, giving trim causes increase of effective power. These results are almost matching wave making resistance shown in Fig. 5.

Propulsive efficiency shows the similar tendency to effective power. Moreover, propulsive efficiency for draft 8.3 m is improved.
by trim by head as well as that for draft 7.6 m. On the other hand, trim by stern does not contribute to improvement in propulsive efficiency irrespective of draft since trim by stern causes increase of resistance and decrease of self-propulsion factors.

Brake power is reduced by trim by head for draft 7.6 m and 8.3 m while there is no reduction in brake power for draft 9.0 m. For draft 7.6 m, both effective power and propulsive efficiency are improved. Maximum 7% reduction rate of brake power at low speeds is shown. Taking into account that there is physical constraint due to avoidance of propeller immersion, optimum trim for draft 7.6 m available in service is trim by head 1.0 m. For draft 9.0 m, trim by head or stern gives larger brake power since both effective power and propulsive efficiency are minimized for no-trim condition. This is reasonable because the vehicle carrier is optimum designed for draft 9.0 m with no trim.

In order to serve the above information to ship operation for various draft conditions usually depending on the amount of cargo, it is convenient to make a trim chart such as shown in Fig. 14, which indicates percentage of power reduction. Hence, optimized trim can be determined for required ship speed at scheduling stage of navigation plan.
4. Discussion

Brake power is estimated as is shown in Eq. (4). Trim variation contributes to change the components in Eq. (4) and results in increase or decrease of brake power. The effect of each component on brake power is calculated by Eq. (8) and shown in Fig. 15 to Fig. 17.

\[
\Delta P = \sum_i \left( \frac{1}{P} \frac{\partial P}{\partial x_i} \delta x_i \right) \times 100 \tag{8}
\]

where \(\Delta P\) is increase rate of change in brake power defined as Eq. (7), \(P\) is brake power under no-trim condition, \(x_i\) is a component expressed as follows which effects on brake power, \(\delta x_i\) is change of \(x_i\) from no-trim condition.

- wetted surface area \(S\)
- form factor \(K\)
- wave making resistance \(C_w\)
- thrust deduction coefficient \((1-t)\)
- effective wake coefficient \((1-w_M)\)
- relative rotative efficiency \(\eta_R\)

The abscissa does not mean rate of change but indicates contribution ratio of the individual component to brake power. The component in negative area means that it contributes to reduction of brake power, and vice versa. The summation of contribution ratio of the component matches rate of change in brake power. Contribution ratio of frictional resistance coefficient of a corresponding plate and that of roughness allowance is quite smaller than the other component so that these are omitted. Taking into account that propeller efficiency is a function of advance speed \(J\) which is calculated by wetted surface area, total resistance coefficient, thrust deduction factor, and effective wake coefficient, its contribution ratio is included in such components.

It is found that trim by head leads to decrease of wetted surface area and that clearly contributes to reduction of resistance regardless of draft. For draft 7.6 m and 8.3 m, wave making resistance and effective wake coefficient are improved by trim by head whilst change in form factor contributes to increase of brake power. This indicates that reduction of brake power is achieved by means of trim by head even though the contribution of wetted surface decrease is excluded.

![Fig. 15 Contribution ratio to brake power at mid. draft 7.6 m (up to down: trim = -2.0 m, -1.0 m, 1.0 m)](image1)

![Fig. 16 Contribution ratio to brake power at mid. draft 8.3 m (up to down: trim = -2.0 m, -1.0 m, 1.0 m)](image2)
Wave making resistance for draft 7.6 m and 8.3 m with trim by head 1.0 m become worse at some speeds since the location of hump and hollow of wave making resistance curve is different. Increase of brake power due to trim by stern is caused by decrease of wave making resistance and effective wake coefficient, and increase of wetted surface area, which is remarkable for draft 9.0 m. For such draft, whether trim is by head or by stern, wave making resistance is predominant for increase of brake power and reduction of brake power cannot be expected. This agrees the fact that the vehicle carrier is optimum-designed with no trim for draft 9.0 m.

5. Conclusions

This study addresses trim optimization for fine ship such as a vehicle carrier and a container ship and investigate the potential for fuel saving by trim optimization. Model tests are conducted for various draft and trim conditions in order to investigate the effect of trim on resistance and self-propulsion factors which are given for estimation of brake power. It is clarified that the optimized trim differs among drafts. Authors concluded that:

(1) Both for vehicle carrier and the container ship, trim by head decreases effective power at low speed for shallow draft, since wave making resistance become smaller due to significant impact of the bulbous bow, which can be considered common tendency for fine ships.

(2) Irrespective of draft, trim by stern increases effective power due to increase of wetted surface area and wave making resistance.

(3) Significant effect of draft on form factor is found. With respect to effect of trim, form factor of the vehicle carrier goes smaller in proportion to increase of trim by stern while that of the container ship shows almost constant.

(4) Propulsive efficiency is improved for draft 7.6 m and 8.3 m due to trim by head whilst for draft 9.0 m the best propulsive efficiency is obtained under no-trim condition. It is shown that shallow aft draft can improve effective wake coefficient. It seems that having trim by head may strengthen the extent of separation of viscous flow on bottom and that shallow aft facilitates inflow of viscous flow into propeller.

(5) Clear effect of trim on thrust deduction coefficient and relative rotative efficiency cannot be found.

(6) Trim by head can reduce brake power and can be expected as means of fuel savings at low speed for shallow draft. In this study optimum trim for shallow draft of the subjected vehicle carrier is trim by head 1.0 m which can be adapted to ships in service. For design full load draft it is natural that no-trim condition is optimum since ship is usually designed for such condition.

References


