Study on trim optimization for an oil tanker

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Abstract. The purpose of this paper is to study the influence of trim on resistance performance for an oil tanker. First, the three-dimensional ship model, calculation basin and structural mesh were obtained. Commercial code of computational fluid dynamics was utilized to calculate the resistance of target ship under various trim conditions and drafts. Then, we compared the results calculated by numerical simulation with the towing tank test results to validate effectiveness of CFD method. Finally, influence of trim on ship resistance performance was analysed. It is concluded that this method can find the optimal trim value and provide practical advice for actual operation of the real ship. Consequently, it can be used to improve the efficiency of energy-saving and emission reduction, which provides a new direction for the development of green ships.

1. Introduction
In recent years, with the continuation of low freight rate and high oil prices in the shipping industry, many ship owners begin to reduce operating costs to improve their market competitiveness. It is estimated that in the life cycle of a ship, fuel-related costs account for about 40% - 60% \cite{1} of the total operational cost. In addition, the International Maritime Organization (IMO) also introduces the energy efficiency design index (EEDI) and operation index (EEOI) to limit carbon dioxide emissions. Therefore, it is of vital importance to reduce the oil consumption for ships.

Optimization of ship's hydrodynamic performance has been an important research topic of energy saving and emission reduction for many years. It mainly includes the following four aspects: optimization of ship hull line, renovation of bulbous bow, installation of energy saving devices, and trim optimization. Of all these measures, ship trim optimization has gained more and more attention for its effectiveness and flexibility for better energy to reduce emissions. Trim optimization is based on the fact that at the same speed and draft, ship experiences different hydrodynamic resistance with different geometric shape of underwater part. So, it is of great possibility that a ship can reach its minimum resistance condition by just adjusting the trim value without making any changes to ship hull form or installing any energy-saving appendages. Besides, it can be applied to not only the operated ships, but also the design process of a ship.

The purpose of this paper is to perform trim optimization for an oil tanker by using CFD method in conjunction with towing tank test. Computational fluid dynamics code was employed to obtain resistance values of the oil tanker in different trim conditions and drafts. Then the numerical method was validated by comparing calculation results with experimental results. Based on the attained results,
the optimum trim conditions of different drafts are suggested. This study testified the effectiveness of using CFD tools in ship trim optimization, which provide a new direction for green ship research.

2. Numerical method

2.1. Ship model

A 46000 DWT product oil tanker has been selected as research target, because it has many loading conditions with various combinations of different drafts and trims during actual operation. Therefore, it has great possibility to achieve better energy efficiency through trim optimization. Principle dimensions of the ship are shown in Table 1.

| Parameters                          | Dimensions (full scale) |
|-------------------------------------|-------------------------|
| Length overall (m)                  | 184.95                  |
| Length between perpendiculars (m)   | 176                     |
| Molded breadth (m)                  | 32.2                    |
| Molded depth (m)                    | 18.2                    |
| Design speed (kn)                   | 11                      |
| Design draft (m)                    | 10.2                    |
| Block coefficient                   | 0.809                   |

Table 1. Principle dimensions of 46000t product oil tanker.

As the oil tanker has many loading conditions during actual operation, in order to improve calculating efficiency, three typical drafts (ballast, design and fully load) are selected as calculation mode to study the influence of trim on ship resistance. The detailed calculation conditions are shown in Table 2. The value of trim means difference between fore and aft draft, and trim by the bow is negative, trim by the stern is positive.

| Case number | Mean draft (m) | Displacement (t) | Trim value (m) |
|-------------|----------------|-----------------|----------------|
| 1.ballast   | 7.8            | 35842           | -1, -0.5, 0, 0.5, 1, 1.8, 2.5, 3 |
| 2.design    | 10.2           | 47932           | -2, -1.3, -0.6, 0, 0.6, 1.3, 2.5, 3 |
| 3.fully load| 11.5           | 54747           | -2, -1.3, -0.6, 0, 0.6, 1.3, 2.5, 3 |

Table 2. Calculation conditions of the oil tanker (full scale).

2.2. Governing equations

The Reynolds Averaged Navier-Stokes equation is a universal governing equation both for kinematics and dynamics of viscous fluid [2], and it is used as basic formula to achieve the fluid field solution.

\[
\rho \frac{Df_i}{Dt} + \frac{\partial}{\partial x_j} \left[ \mu_j \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \mu_0 \frac{\partial}{\partial x_j} \delta_{ij} \right] +
\]

\[
\frac{\partial}{\partial x_j} \left( -\rho u_i u_j \right) - \frac{\partial p}{\partial x_j} = \frac{\partial (\rho u_i)}{\partial t} + \frac{\partial}{\partial x_j} \left( \rho u_i u_j \right)
\]

(1)

Where \( \rho \), \( p \), and \( f_i \) are fluid density, static pressure, and mass force respectively, \( u_i, u_j \) represent the time-averaged velocity components (i, j = 1, 2, 3).

The turbulence model RNG \(-k - \varepsilon\) is used to close RANS equations for its advantages in simulating secondary flow such as separated flow and complex flow around ship hull.
2.3. Grid generation and boundary condition

Grid generation is an important process in CFD simulation, and it is also one of the key factors affecting the simulation accuracy, stability and convergence speed of numerical calculation. In this paper, the free-surface model is used to calculate total resistance of ship model [3-4]. The grid system is the hexahedron grids of H-O type in a multi-block [5-7]. The number of hexahedral cells is about 1.1 million. Figure 1 shows grid distribution of computational domain.

![Figure 1. Grid of computational domain.](image)

The calculation domain consists of inlet plane, outlet plane, symmetry plane, ship hull, side plane, top plane and bottom plane. The inlet and outlet plane are at a distance of $1L_{pp}$ and $2L_{pp}$ front and behind the hull, the side plane and bottom plane are at a distance of $1L_{pp}$ and $0.5L_{pp}$, respectively. As for the boundary conditions, we apply velocity inlet, pressure outlet, symmetry and no slip shear conditions for the inlet plane, outlet plane, symmetry plane and ship/side/bottom boundary surfaces. The standard wall function is introduced to improve calculation efficiency. The VOF multiphase-flow model is used to capture the fluctuation of free surface.

\[
\frac{\partial a_q}{\partial t} + \frac{\partial (u_i a_q)}{\partial x_i} = 0 \quad (q = 1, 2)
\]

Where $a_1$, $a_2$ are volume fraction of air and water, respectively.

3. Validating of numerical method

In order to validate the reliability of CFD method in resistance prediction, we compare the calculation results with model test data. The towing tank model test was carried out at the Key Aviation Scientific and Technological Laboratory of High Speed Hydrodynamic. Principle dimension of the tank is $510m \times 6.5m \times 5m$. The maximum carriage velocity is $25 m/s$. The model scale $\lambda = 36$ is determined by the width of the pool, the highest speed of the trailer, and the speed of the real ship. A boundary layer trip is installed near the 19 station to keep flow around the ship model in a turbulent state.

Comparison results of numerical method and experimental data are shown in Table 3 and Figure 2, where $R_m$ and $R_s$ represent the test data and numerical data, energy-saving efficiency means proportion of resistance reduction comparing with even keel condition for the same draft.

It can be seen from Table 3 and Figure 2 that the calculation results are in reasonable agreement with experimental values, with the maximum prediction error equals to 6.12%. Besides, trend of resistance variation with trim value of computational prediction is similar to that of the test data, which indicates that the numerical method can be applied to the calculation of the oil tanker’s resistance prediction.
### Table 3. Comparison of ship model resistance at design speed between CFD and experiment.

| Mean draft (m)     | Trim (m) | $R_m$ (N) | $R_s$ (N) | Error of CFD Method (%) | Energy-saving efficiency (%) |
|--------------------|----------|-----------|-----------|-------------------------|-----------------------------|
| ballast draft=0.217| -0.03    | 10.28     | 10.53     | 2.43                    | 2.14                        |
|                    | -0.01    | 10.22     | 10.49     | 2.64                    | 2.51                        |
|                    | 0.00     | 10.58     | 10.76     | 1.70                    | 0.00                        |
|                    | 0.01     | 10.91     | 11.33     | 3.85                    | -5.30                       |
|                    | 0.03     | 11.13     | 11.37     | 2.16                    | -5.67                       |
|                    | 0.05     | 11.29     | 11.45     | 1.42                    | -6.41                       |
|                    | 0.07     | 11.34     | 11.77     | 3.79                    | -9.39                       |
|                    | 0.08     | 11.46     | 11.69     | 2.01                    | -8.64                       |
| design draft=0.283 | -0.06    | 12.26     | 12.65     | 3.18                    | 6.02                        |
|                    | -0.04    | 12.52     | 12.89     | 2.96                    | 4.23                        |
|                    | -0.02    | 12.61     | 12.97     | 2.85                    | 3.64                        |
|                    | 0.00     | 13.04     | 13.46     | 3.22                    | 0.00                        |
|                    | 0.02     | 13.39     | 13.64     | 1.87                    | -1.34                       |
|                    | 0.04     | 12.63     | 12.85     | 1.74                    | 4.53                        |
|                    | 0.07     | 12.87     | 12.98     | 0.85                    | 3.57                        |
|                    | 0.08     | 13.08     | 13.46     | 2.91                    | 0.00                        |
| fully load draft=0.319 | -0.06  | 12.82     | 13.31     | 3.82                    | 15.65                       |
|                    | -0.04    | 12.74     | 13.42     | 5.34                    | 14.96                       |
|                    | -0.02    | 12.62     | 13.18     | 4.44                    | 16.48                       |
|                    | 0.00     | 14.88     | 15.78     | 6.05                    | 0.00                        |
|                    | 0.02     | 14.38     | 15.26     | 6.12                    | 3.30                        |
|                    | 0.04     | 14.00     | 14.41     | 2.93                    | 8.68                        |
|                    | 0.07     | 14.06     | 14.65     | 4.20                    | 7.16                        |
|                    | 0.08     | 14.10     | 14.90     | 5.67                    | 5.58                        |

**Figure 2.** Comparison curves of calculation and experimental results.
4. Influence of trim on ship resistance
As can be seen from Figure 2, the resistance versus trim plot shows that trim can cause significant influence on ship total influence. For the ballast draft, where the bulb is exposed above the surface, the optimum trim point is 0.01m trim by the bow. Total resistance in the bow trim condition is smaller than that in even keel condition, the resistance increases as stern trim value enlarges, and trim by the bow is profitable for resistance reduction, this phenomenon implies that reducing the interaction between free surface and bulbous bow is favorable for resistance performance when the ship has a shallow draught.

When the ship operates at the design draft, trim by the bow is still effective since the resistance decreases while the bow trim value increases. The optimum trim condition of this draft is 0.06m bow trim, and it can achieve about 6% of energy saving efficiency. However, resistance variation of this draught has no obvious correlation with stern trim value, with trim by the stern could cause reduction as well as increase of ship resistance.

Figure 3 shows distribution of dynamic pressure along ship hull surface at different trim conditions. It can be seen that the pressure gradually increase from 0.02m bow trim to 0.02m stern trim at the front part of ship, this is because wave-making is largely affected by the underwater area of a ship, and trim has changed the wetted surface. When the ship trims 0.02m by the bow, wave-making of bulbous bow and ship hull generates favorable interference, and amplitude of sympathetic wave decreases significantly, which has caused deduction of wave making resistance component.

![Figure 3. Dynamic pressure of different trim conditions at design draft.](image)

When the bulbous bow immersion continues to get deeper, even keel condition should be avoided because the total resistance reaches a maximum value under this condition. The optimal trim condition occurs at 0.02m bow trim, with the energy-saving efficiency reaches 15.65%. At this draft, resistance of bow trim condition is smaller compared with stern trim, so, stern trim should be avoided during actual operation.

5. Conclusion
Faced with the pressure of rising oil price as well as environmental regulations introduced by IMO and other companies, trim optimization has become a wildly used energy conservation measure for its flexibility and simplicity in actual operation compared with other traditional strategies.

In this paper, investigation over the influence of trim on a product oil tanker's resistance has been made. The numerical simulation technique is applied to obtain total resistance of target ship, and its reliability is verified by towing tank model test data. As the immersion depth of bulbous bow can cause significant change on a ship's hydrodynamic performance (especially wave making resistance), three typical drafts of different trim conditions at design speed are selected to carry out the study. When the
ship has a shallow draught, the optimal trim condition occur at 0.01m bow trim, stern trim should be rejected as the ship experiences the largest resistance compared with other conditions, and the total resistance increases along with the stern trim value. At design drafts, the optimal trim condition is 0.06m bow trim, but the resistance can be smaller as well as bigger than the even keel state when the ship has a stern trim condition. While when the ship reaches its maximum draft, bow trim and stern trim are more favourable compared with even keel condition.

This study confirms that trim can have a significant impact on total resistance, and it can be expected that this study can give hull form optimizer and ship operator some useful information for energy conservation and emission reduction.

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