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ON THE PREDICTION OF SHIP PERFORMANCE IN ACTUAL SEA CONDITIONS USING COMPUTATIONAL FLUID DYNAMICS

Hiromichi Akimoto[1]

[1]Department of Systems Innovation, Graduate School of Engineering, The University of Tokyo, Japan
E-mail: akimoto@sys.t.u-tokyo.ac.jp

ABSTRACT

Towing tank test is a common tool for the research and development of ships. However, experimental conditions of a towing tank are usually limited to head wave conditions and symmetry motion of the ship. Although there is a strong demand for higher economical efficiency of commercial vessels, we do not have effective tool for predicting the performance of planned vessel in the actual operating conditions. In this research, the author use computational fluid dynamics (CFD) simulation to reproduce the unrestricted motion of the ship in oblique waves to investigate the influence of the freedom of motion to the total resistance of ship. The results indicate that additional degrees of freedom in motion (roll and sway) and the drag from rudder action might have significant influence on the performance of ship in oblique wave conditions.

Key words: Computational Fluid Dynamics, CFD, actual sea condition, sea margin, oblique wave, 6DOF

1. INTRODUCTION

Although ship is a transportation mode of low energy consumption, reduction of green house gasses emission and fuel consumption of sea transportation is an important issue because of its vast transportation volume. However, prediction of the performance of a planned ship in actual sea environment is still a difficult task.

The main tool for evaluating the resistance of a ship before its construction is towing tanks. We can generate waves to imitate the sea environment and obtain the motion and resistance of the vessel. However, their experimental conditions are limited to head wave conditions and symmetric ship motions, i.e., heave, pitch and surge because of the mechanical restriction of towing tests. Since we do not select head sea course in actual operations, the experimental data of towing tanks might provide inaccurate information for the improvement of hull design. Although maneuvering tanks provide more freedoms in ship motion, it is still difficult to obtain reliable performance data because of the mechanical restriction and the limited size of model ships.

When a ship takes oblique course to incident wave, it experiences asymmetric wave load and shows asymmetric motions in roll, sway and yaw direction. In addition, the ship has non-zero leeway and rudder angles to cancel the asymmetric force and moment to keep its course on oblique waves. However, we are using empirical "sea margin" to predict the increase of drag in actual operation only because we do not have alternative tools for the purpose. Tsujimoto et al. [1] and Hulskotte et al. [2] showed the increase of fuel consumption in actual operations and the procedure of its prediction. Tsujimoto et al. proposed "ten-mode for marine transportation" for the fuel economy indicators of ships in actual operating condition [3]. It is similar to the fuel economy test cycle of automobiles. It means there is increasing demand of predicting practical fuel economy of ships.

With the recent progress of computational fluid dynamics (CFD) technique, we can perform Reynolds averaged Navier-Stokes (RaNS) simulation of a ship in waves. However, applications of RaNS simulation are usually imitations of towing tank experiments. Since CFD simulation does not have mechanical restrictions in obtaining ship motion, it has good potential for predicting performance of ships with unrestricted motion on waves. This paper describes an attempt of numerically evaluating sea-margin of ships using CFD simulations.

2. COMPUTATIONAL METHOD

2.1 RaNS solver

We use Reynolds averaged Navier-Stokes (RaNS) simulation code WISDAM-X that is developed by Orihara et al. [4] in The University of Tokyo. The code is designed for solving time-dependent interaction between a ship and free surface flow with finite volume method (FVM). Summary of the characteristics of code is as follows.

- Governing equations

  - ➢ Reynolds-averaged Navier-Stokes (RaNS) equation
  - ➢ Continuous equation
- Pressure solution algorithm
  - ➢ Pressure solution of Marker-and-Cell (MAC) method.
- Spatial discretization
  - ➢ 3rd order upstream (advection term)
  - ➢ 2nd order central (other terms)
- Free surface treatment
  - ➢ Marker Density Function method
- Time discretization
  - ➢ 1st order Euler explicit
  - ➢ Adams-Bashforth (2nd order for marker density)
- Arrangement of variables in the control volume
  - ➢ Staggered arrangement of velocity components
- Turbulence model
  - ➢ Baldwin-Lomax 0-eq model
  - ➢ Dynamic subgrid scale (DSGS) model

We employ Baldwin-Lomax model and Dynamics SGS (DSGS) model to evaluate the turbulent viscosity in the flow field. Local turbulent viscosity is determined by the weighted average of these two models. Free surface is modeled by the density function method.

2.2 Overset grid technique

To provide adequate spatial resolution both on free surface and in the boundary layer around the hull, we use structured overset grids as shown in Fig. 1. The outer domain has fine spatial resolution around the water surface to simulate incident waves. The mesh of the inner domain is boundary fitted one to provide fine resolution in the boundary layer. Fig. 2 shows the exterior boundary and hull surface of inner mesh on the free surface.

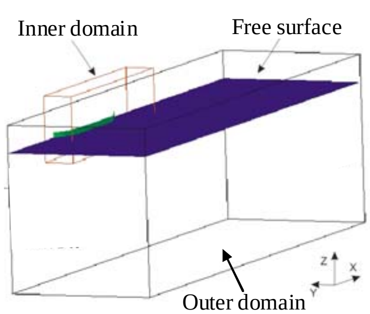

Figure 1: Overset mesh layout (in symmetry condition)

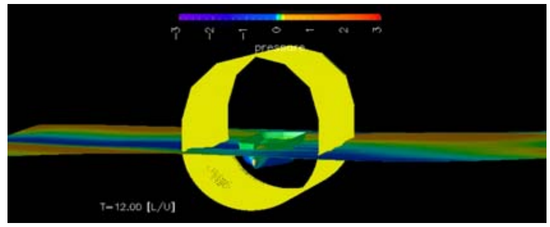

Figure 2: Free surface and the exterior surface of the inner domain.

Computation in the inner domain is on the moving coordinate fixed on the ship in motion. The motion of ship with six-degrees of freedom (6DOF) in motion is solved using the hydrodynamic forces and moments provided by the flow simulation. On the exterior surface of inner mesh, trilinear interpolation of outer flow variables gives boundary condition of inner domain, vice versa.

2.3 Model of rudder

In oblique wave conditions, a ship requires adjustment of rudder angles so that it has appropriate leeway angle and cancel the asymmetric load from waves (Fig. 3). However, simulating the rudder control in CFD is time consuming. Therefore, in the present analysis, we perform a series of CFD simulations without rudder by changing leeway angle, and determine the balanced condition of the ship using the interpolation of simulation results. The action of rudder is modeled as a finite span NACA0018 wing with aspect ratio 1.66. The force on the rudder is determined by experimental data of finite span wing [5] with correction of the aspect ratio. The present analysis does not include interference between the rudder and flow field around the hull.

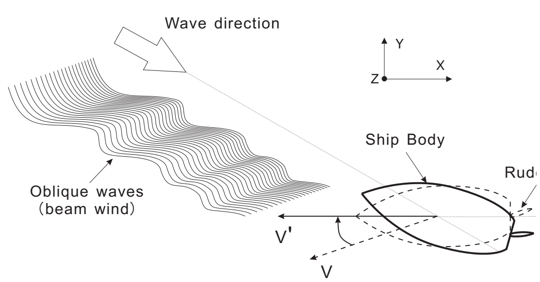

Figure 3: Condition of a ship in oblique wave condition.

3. RESULTS AND DISCUSSION

3.1 Four DOF motion on oblique waves

We conduct simulations of SR221 (VLCC, L_{pp}=320m) and SR108 (container carrier, L_{pp}=175m) on oblique waves. Conditions of simulation are shown in Table. 1. The direction of incident wave is 120 degree (waves come from starboard ahead), wave amplitude is 1% L_{pp} and wave length $0.5L_{pp}$. It is equivalent to Beaufort wind force scale 9 for SR221 and 7 for SR108. Fig. 5 shows a visualization sample of SR108 with roll and sway motion.

Table 1: Condition of simulations

Num. grids in inner and outer domains	Inner: 130x21x139 Outer: 146x61x41
Minimum grid spacing	0.001
Reynolds number	1.0×10^6
Froude number	0.151 (SR221) 0.275(SR108)
Wave direction	120 deg.
Wave length	0.5 L_{pp}
Wave amplitude	1% L_{pp}

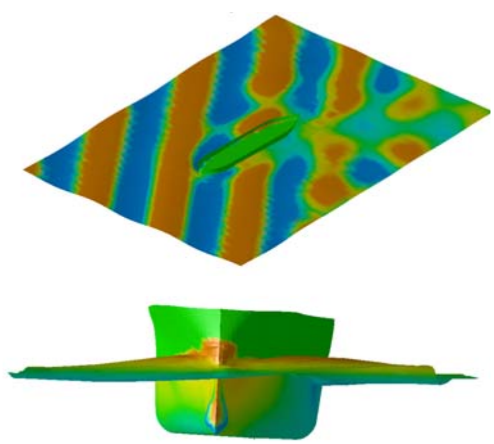

Figure 4: Overview of the computational domain and front view of the ship: SR108 ship with 4DOF in motion.

Figures 5 and 6 show the time histories of roll angle and sway velocity of SR221 with different leeway angles ranging from -3 to 0 degree. In the time histories, incident wave starts at non-dimensional time T=8. The ship shows oscillating motions of roll and sways in addition to heave and pitches ones.

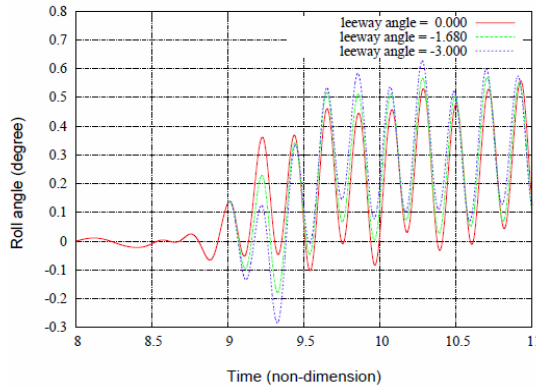

Figure 5: Time histories of roll angle in different leeway angles.

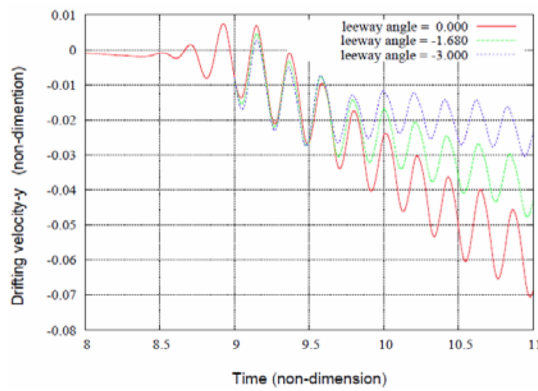

Figure 6: Time histories of roll angle in different leeway angles.

In Fig. 6, lateral force does not balance and the ship starts drifts. To obtain the appropriate leeway and angles for keeping the course of ship, we solve the following system of equations with simplification:

$$\begin{cases} F_y^{hull}(\beta) + F_y^{rudder}(\delta) = 0 \\ M_z^{hull}(\beta) + M_z^{rudder}(\delta) = 0 \end{cases} \quad (1)$$

Here, β and δ are leeway (yaw) and rudder angles of the ship respectively. $F_y^{hull}(\beta)$ and $M_z^{hull}(\beta)$ are lateral force and yaw moment acting on the hull obtained from CFD. The rudder model determines the force $F_y^{rudder}(\delta)$ and yaw moment $M_z^{rudder}(\delta)$. The solution of (1) gives the approximated set of leeway and rudder angles in the given wave condition.

Figures 7 and 8 show the increase of total drag in different DOFs and leeway angles. In these figures we are using abbreviated names of DOF conditions. For example, HP means that heave and pitch motions of the ship are free in the simulation, and HPRS means heave, pitch, roll and sway motions are free. Hull and rudder components of drag are separately shown as the relative increase from the basis of HP condition. Although the simulation is capable of solving all 6 DOF motion of the ship, we restricted sway and surge motions for simplicity.

Fig. 5 (SR221) shows the slight increase of hull drag with the increased freedoms in motion. In HPRS condition, increase of both hull and rudder drag components are significant. The increase of hull drag in HPRS condition is 5% from the base resistance of HP while the increase of rudder drag is 8%. In total, added motions of roll and sway lead to 13% increase of total drag. In the case of SR108, tendency of drag is less significant. However, it shows complicated dependency to leeway angle. With the increase of leeway, hull drag component decreases while drag from the rudder increases. The present results show complicated behavior of total resistance in different mode of motion and the large influence of rudder drag in oblique wave conditions. It also implies that reducing lateral force and the change of yaw moment in oblique wave condition lead to improvement of economic performance when modification of the hull shape is possible.

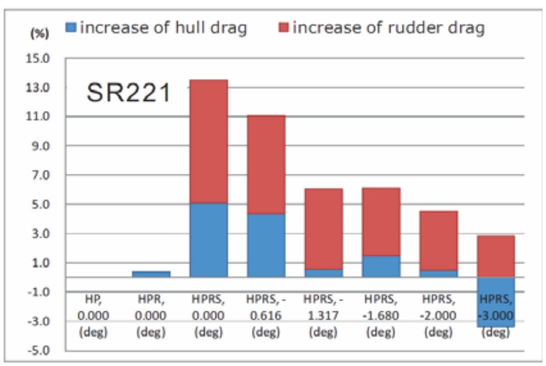

Figure 7: Increase of total drag on oblique waves in different DOF and leeway angles: SR221 VLCC model.

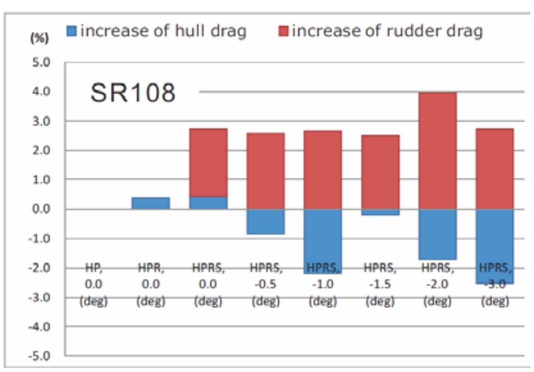

Figure 8: Increase of total drag on oblique waves in different DOF and leeway angles: SR108 container carrier model.

4. CONCLUSION

To investigate the increase of resistance in actual operating condition, we conducted CFD simulations of a ship with different degrees of freedom in motion on oblique waves. The results show that the increase of resistance depends on the asymmetric motion of the ship and rudder action. It also means that the improvement of performance in usual towing tank tests does not assure higher performance of the ship in actual operation.

Present simulation does not contain yaw and surge motions those might have higher influence on the total resistance. For further investigation, we are going to include time-dependent steering model in the present simulation and extend the wave conditions to two directional and irregular waves.

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