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Seakeeping optimization of trimaran outrigger layout based on NSGA-II

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ABSTRACT

The outrigger layout of a trimaran has a significant influence on its seakeeping performance. In this paper, the high-speed slender body potential flow theory (also named the 2D+t theory or 2.5D method) is applied to trimaran seakeeping calculations. A series of ship motion experiments were carried out in head regular waves for one trimaran with different outrigger layouts at the Froude numbers of 0.471 and 0.628. The experimental results have been compared with the simulation results derived from a 2.5D seakeeping prediction program to validate the 2.5D method. The enumeration method is used to study the influence of the outrigger layout on the seakeeping performance. Furthermore, the contour maps of the heave, pitch and roll motions are plotted at different forward speeds (Fn = 0.4 and Fn = 0.5). To improve the seakeeping performance of a trimaran in waves, a fast elitist non-dominated sorting genetic algorithm (NSGA-II) is adopted in this paper. Moreover, this paper proposes a fast optimization method for the trimaran outrigger layout by combining NSGA-II with the 2.5D seakeeping predicting method. Finally, taking a trimaran as an example, this paper provides the optimal outrigger layout with the minimum heave, pitch and roll motion.

1. Introduction

Trimarans, being high-performance ships, have attracted more and more people's attention in recent years. Trimarans have a lower resistance (in some ranges of Froude numbers) and a better transverse stability compared with conventional monohull ships due to their unique configuration. In the past years, many investigations of trimarans based on ship resistance and seakeeping performance have been performed. With regard to resistance, Wilson [1] proposed the idea of cancelling waves between hulls by designing the outrigger layout properly to reduce the wave-making resistance of the whole ship. Thereafter, Suzuki et al. [2] and Yeung et al. [3] studied the influence of outrigger layout on wave resistance by linear wave resistance theory.

In terms of seakeeping performance, Francescutto [4] studied the numerical model for the roll motion of a trimaran and validated it by comparing it with the experimental results. The main drawback of his work is that the calculating model ignores the exciting force on outriggers. Hence, although the numerical model is simple in calculation, its calculation process is not sufficiently strict. Bingham [5] calculated the wave load and motion of a trimaran in regular waves by the three-dimensional pulsating source potential-flow method, three-dimensional translating-pulsating source potential-flow method and coupled hydroelastic theory. Duan et al. [6] calculated the vertical motions of a trimaran in different Froude numbers using two-dimensional plus time dependent theory (2D+t or 2.5D). They demonstrated that the results of the 2.5D method for the trimaran wave-induced motion predictions are in agreement with the experimental results.

For the experimental study of a trimaran, Bertorello et al. [7–9] made some important contributions to trimaran experimental research at the beginning of the 21st century. In their works, model tests on multiple trimarans are carried out, and the influences of trim, hull form and outrigger layout on the resistance and seakeeping performance of trimarans are deeply analysed. In addition, Hebblewhite et al. [10] carried out experiments, discussed the seakeeping performance of trimarans and pointed out that a trimaran's seakeeping performance can be improved by properly designing the outrigger layout.

With respect to the ship hydrodynamic performance optimization, the enumeration method (a method of listing all the items in a collection) is traditionally used for the trimaran outrigger layout optimization. However, this method not only has low calculation efficiency but also may not obtain the true global optimal value because of missing the proper choices from the discrete samples. When considering the optimization with the purpose of improving the seakeeping performance for trimarans, there is usually more than one optimization objective (e.g., heave, pitch, roll, etc.). Hence, the conventional single objective genetic algorithm is not suitable for this problem, and a multi-objective optimization method is therefore suitable. Kim [11] discussed the applicability of various optimal methods in monohull ship hull form optimization by means of comparing the results of four optimization methods. The study showed that for the ship seakeeping and resistance

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Nomenclature

a	longitudinal distance between outrigger stern and main hull stern (unit:m)
p	distance between longitudinal section of outrigger and mainhull (unit:m)
f_v^i	virtual fitness of the ith individual
Fn	Froude number
k	wave number
L	Length of waterline (whole ship unit:m)
N_j	normal vector on the boundary of ship transverse section
U	forward speed
λ	wave length (unit:m)
ς_a	wave amplitude (unit:m)
cr_h	critical coefficient of heave motion
cr_p	critical coefficient of pitch motion
cr_r	critical coefficient of roll motion
m_j	interference effect of steady potential to unsteady potential
w_k	weighting coefficient of heave motion
w_p	weighting coefficient of pitch motion
w_r	weighting coefficient of roll motion
η_{3a}	amplitude of heave motion (unit:m)
η_{5a}	amplitude of pitch motion (unit: rad)
η_h^i	heave response function of the ith individual
η_p^i	pitch response function of the ith individual
η_r^i	roll response function of the ith individual
ϕ_0	velocity potential of incoming wave with unit amplitude
ϕ_j	radiation potential of ship in j mode motion with unit amplitude
ϕ_7	diffraction potential under incoming wave with unit amplitude
ω_e	encounter frequency
α	wave heading
σ	convergence factor

optimization problem, the multi-objective genetic algorithm provides satisfactory results. Tahara et al. [12] optimized a fast catamaran (HSSL-B) through a simulation-based design (SBD) framework. In their work, some multi-objective optimization problems of catamarans were successfully solved by combining a high-fidelity solver (URANS solver) with global optimization algorithms. The obtained optimal designs were in agreement with the experimental results. In terms of the optimization algorithm, Srinivas and Deb [13] first proposed a non-dominated sorting genetic algorithm (NSGA), which is based on the concept of Pareto efficiency (which will be explained in Section 6). NSGA is one kind of multi-objective genetic algorithm and has been widely used in many fields since it was published. Subsequently, Deb et al. [14] improved NSGA and proposed a non-dominated sorting genetic algorithm with elitist strategy (NSGA-II) that improves the calculation efficiency of the algorithm.

In this paper, the 2.5D method is used to predict the seakeeping performance of a trimaran in head-sea waves, and the method is validated by experimental data. The enumeration method combined with the 2.5D numerical method is applied to study the influences of the outrigger layout on the seakeeping performance of a trimaran at different forward speeds in regular head-sea and oblique waves. On this basis, this paper proposes a fast optimization method of the trimaran outrigger layout with the purpose of optimal seakeeping performance by means of combining NSGA-II with the 2.5D method, which provides a basis for subsequent optimization with other factors (resistance, manoeuvring, structural strength, etc.) being taken into account. The high computational efficiency characteristics of this method are demonstrated by optimizing a trimaran outrigger layout in this paper.

2. Trimaran motion prediction by using 2.5D theory

High-speed slender body potential flow theory, also called two and a half dimensional potential flow theory (2D + t or 2.5D), was first used by Faltinsen and Zhao [15] for the theoretical prediction of ship seakeeping performance. This method effectively overcomes the shortcomings of the STF method [16] (Salvesen, Tuck and Faltinsen) in the prediction of multihull ship seakeeping, as the STF method has difficulty in accurately considering the hydrodynamic interference effect between hulls in a multihull ship. In addition, compared to the three-dimensional method, the 2.5D method has a higher computational efficiency. Hence, it is a practical method that is suitable for the motion prediction of high-speed vessels [17] and multihull ships.

2.1. The introduction of formulations for 2.5D theory and it's numerical solution

In the 2.5D theory we used, the formulations are linearized upon the free surface and the body surface boundary conditions. This theory uses the following assumptions:

(1) Slender body assumption: the ship hull is assumed to be a slender body (with a high ship length to ship breadth ratio);
(2) The steady wave-making potential is neglected: we neglect the steady wave potential term in the static water;
(3) There are no waves in front of the ship bow: in front of the ship bow ($x > x_0$), there is no unsteady flow field disturbance, which requires $\frac{\omega U}{g} \gg \sqrt{\frac{2}{27}}$ [18].

According to the assumptions above, the unsteady velocity potential around the ship in the ship moving coordinate system satisfies the formulations as below:

$$\begin{cases} \frac{\partial^2\phi_j}{\partial y^2} + \frac{\partial^2\phi_j}{\partial z^2} = 0 \quad \text{In the Flow Field} \\ \left[\left(i\omega_e - U\frac{\partial}{\partial x}\right)^2 + g\frac{\partial}{\partial z}\right]\phi_j = 0 \quad (z = 0) \\ \frac{\partial\phi_j}{\partial n} = \begin{cases} i\omega_e N_j + \mathrm{U}m_j & j = 2-6 \\ -\frac{\partial\phi_0}{\partial n} & j = 7 \end{cases} \quad \text{on the Mean Wetted Hull Surface} \\ \phi_j = \frac{\partial\phi_j}{\partial x} = 0 \quad (x > x_0) \\ \text{Suitable Far Field Radiation Condition} \end{cases} \tag{1}$$

where ω_e is encounter frequency, ϕ_0 is the incident wave potential with unit amplitude, ϕ_j (j = 2-6) is the radiation potential in jth motion mode with unit amplitude, ϕ_7 is the diffraction potential in a unit wave amplitude incident wave. x_0 is the coordinate value of the ship bow along the ship length direction, i.e. ($x > x_0$) represents the area in front of the ship bow area. N_j is the normal vector of the ship transverse section boundary, and m_j is the interference effect of steady potential to unsteady potential, which satisfies $m_2 = m_3 = m_4 = 0$, $m_5 = N_3$, and $m_6 = -N_2$ when neglecting the steady potential. The three-dimensional free surface condition with forward speed is preserved in the free surface boundary condition of Eq. (1). Meanwhile, the unsteady waves at the ship bow are assumed to be zero. To a certain extent, the propagation characteristics of the unsteady waves in the direction of ship length are reflected at the higher forward speed. As the flow field solution is two-dimensional, and the free surface condition is three-dimensional, the above-mentioned linear high-speed slender body