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Multidisciplinary optimization of an offshore aquaculture vessel hull form based on the support vector regression surrogate model

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ABSTRACT

The shape of a ship's hull has a significant impact on the resistance and propulsive performance of the ship, especially for wide ships. In this study, experimental and numerical analyses of an offshore aquaculture vessel were carried out, while multidisciplinary design optimization aimed to improve the resistance performance and the wake field quality of the vessel. Numerical analysis was performed using a Reynolds-averaged-Navier_Stokes (RANS) solver, and the numerical method was validated by comparing the numerical results from the original shape to the experimental results. Three support vector regression (SVR)-based surrogate models with different numbers of sample points were built, and the influence of the sample set size on the prediction precision was determined. An SVR surrogate model with 60 sample points was applied and optimized to replace direct numerical simulations. An optimization framework using Latin hypercube sampling (LHS), the free-form deformation (FFD) method, the SVR surrogate model, and the non-dominated sorting genetic algorithm II (NSGAII) was developed. Nine design variables were employed to modify the shape of the vessel. Because of the trade-off between the minimum resistance and the minimum circumferential nonuniformity of the wake flow, the optimal solution of the hull shape was selected from the Pareto-optimal solutions to balance the two objectives. Model tests for the optimized shape were then performed to validate the design results. The results showed that the resistance and the circumferential nonuniformity of the wake flow of the optimized shape were reduced by 1.59% and 17.80%, respectively, when compared to the results of the original shape.

1. Introduction

The deep sea has good water quality, little terrigenous pollution and disease, and is suitable for deep-sea aquaculture. Among marine power strategies, deep sea aquaculture equipment may experience significant development as a more efficient and greener mode of performing aquaculture. Designing an offshore aquaculture platform could offer great value to China's deep sea aquaculture equipment industry, profoundly impact the overcapacity in the shipbuilding industry, and improve deep sea aquaculture equipment. However, the hull form design of a platform is complex and involves a large number of design variables, complicated constraints, and multiple objectives, and thus it is difficult to determine a globally optimal hull form. Traditionaldesign method is mainly based on the shape of the parent vessel. The hull form is modified to satisfy design objectives on a per-use basis, and theperformance is optimized and verified by model testing. However, traditional optimization methods are expensive and time-consuming, relying too heavily on the form of the parent vessel, model testing, and employment of experienced engineers. Therefore, it is necessary to find a time- and cost-effective optimization method for hull form design.

In the 1970s, optimization theory was introduced into the field of ship design. During this time, ship optimization research focused mainly on the expression of hull geometry and numerical calculation. Hsiung (1972) introduced a set of “tent” functions to approximate the ship hull function. By introducing the functions, the Michell integral for wave resistance was reduced to a standard quadratic form. The quadratic programming techniques were applied to minimize the wave resistance. Three optimal forms were chosen and validated by model tests. It was found that the wave resistance of the ship was reduced significantly after optimization. Huan and Huang (1998) optimized the wave-making resistance by applying a highly efficient gradient-based optimization method combined with the potential flow method. Suzuki

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Nomenclature

V	Flow rate (m/s)
V_m	Ship speed for model scale (m/s)
V_s	Ship speed for actual ship (Kn)
L_{OA}	Overall length (m)
L_{pp}	Length between perpendiculars (m)
L_{wl}	Designed waterline length (m)
B	Ship width (m)
d	Draft (m)
Re	Reynolds number, $Re = \frac{VL_{OA}}{\nu}$
Fr	Froude number, $Fr = \frac{V}{\sqrt{gL_{OA}}}$
λ	Scale ratio
S_m	Wetted surface for model scale (m^2)
R_{tm}	Total resistance for model scale (N)
C_{tm}	Resistance coefficient for model scale, $C_{tm} = \frac{R_{tm}}{\frac{1}{2}\rho V_m^2 S_m}$
Δ	Displacement (MT)
w	Wake fraction

and Iokamori (1999) proposed an elliptical panel arrangement of the free surface panels, and the improved Dawson-type solver was used to report the wave-making resistance of the ship. A weight function was introduced to present the hull as a smooth surface. By means of sequential quadratic programming, optimization of the HTC container ship was carried out to minimize the wave-making resistance and showed good performance. Harries (1998) applied the Lackenby transform method to the LNG ship for the first time. This led to a transformation of the hull shape by changing the sectional area curve of the ship. Harries and Abt (1998) conducted an in-depth study on a proposed method that consisted of a parametric curve and a surface based on the variation differential scheme. Since then, Harries (2001, 2004), Abt et al. (2001), and Valdenazzi et al. (2002) have developed the commercial modeling software FRIENDSHIP (now CAESES) and have performed parametric modeling as well as shape deformation modeling of various ships. The resistance and sea-keeping performance of these ships were predicted based on the panel method and the 2-D strip method. Optimizations of the hull shapes were conducted according to the studies above and produced good results. Han et al. (2012) carried out global shape optimization of an ultra-large container ship and the fore-body hull form optimization of an LPG carrier using an F-Spline based optimization procedure. Verified by model testing, the total resistance of the optimal LNG carrier was decreased by 5.7% and the peak of the bow waves was reduced.

With the development of computer hardware and computational fluid dynamics (CFD), a new design method that combines the viscous CFD method with optimization technology has been gradually rising in popularity. The new design method, simulation-based design (SBD), is a multi-disciplinary, globally oriented design pattern that is rigorously supported by mathematics. The viscous CFD method evaluates the hydrodynamic performance of the target ship. Thus, the target ship is optimized within a given constraint by using geometric reconstruction and optimization technology to obtain the optimal hull shape.

Tahara (1998) applied the RANS solver to optimize the hull form of a tanker. Peri et al. (2001) and Campana et al. (2002) applied the Bezier Patch method on the optimization of a bulbous bow. Taking the amplitude of the bow wave and the total resistance as optimization objectives, a series of traditional optimization methods were used to optimize the model and the results were verified by model testing. Optimization modeling determined that the total resistance could be reduced by 3%, and the amplitude of the bow wave could be reduced by 71%. Peri and Campana (2003, 2005), Tahara et al. (2008), and Campana et al. (2004, 2009a) optimized a scale model of a DTMB5415 ship with the optimization objectives of reducing the wave-making resistance, improving the sea-keeping performance (i.e., reducing the heave and the peak of the pitch angle), and increasing the quality of the wake field. Studies on the variable-fidelity surrogate model, multi-objective global optimization algorithm, Bezier Patch method, and CAD-based geometric reconstruction method were carried out in detail. The optimization results were verified by model testing. The results showed that the total resistance of the optimal ship could be decreased by 5.23% while the wave-making resistance and the quality of the wake flow field were improved. Campana et al. (2006) conducted geometric reconstruction of a bulbous bow using the non-nuiform rational B-spline (NURBS) surface modeling method, and the hydrodynamic performance of the bulbous bow was obtained by solving RANS equations. The bulbous bow was optimized, and the ideal result was obtained. Kim et al. (2010) optimized the Series-60 model using a geometric reconstruction method combined with the Lackenby method and the radial basis function (RBF). The results showed that a better resistance reduction effect was obtained by applying the blending geometric reconstruction method.

In order to minimize the computation cost while maintaining adequate optimization and accuracy, scientists have also researched optimization strategies, for example, by using a surrogate model to improve optimization algorithms. Peri and Campana (2006) and Tahara et al. (2008) applied the multi-objective genetic algorithm (MOGA) and a hybrid algorithm combing particle swarm optimization (PSO) and the diagonal rectangular algorithm for global optimization (DRAGO) for the optimization of a high-speed catamaran. A single target (resistance at one sailing speed), a weighted single target (weighted resistance at three different sailing speeds), and multiple targets (resistance and sea-keeping performance) were set as the optimization objectives. The free-form deformation (FFD) method and the CAD-based method were used for geometric reconstruction of the hull. The results showed that the resistance, heave peak, and roll peak of the optimal design were reduced by 9.3%, 50.5%, and 27.4%, respectively. Pino et al. (2007) proposed the deterministic particle swarm optimization (DPSO) algorithm on the basis of the PSO algorithm. The results showed that the new algorithm could achieve better optimization results. Peri et al. (2008, 2009) analyzed the impact of a surrogate model on calculation accuracy and time cost. They determined that using a surrogate model could greatly reduce the time cost of optimization while still ensuring the accuracy of the optimization results. Thus, the trade-off between the accuracy and efficiency of optimization could be well balanced. Campana et al. (2009b) proposed the deterministic derivative-free particle swarm optimization (DDFPSO) to solve multi-objective global optimization, and the algorithm was tested by standard functions. The results showed that the improved algorithm could reach the global optimal solution more efficiently and accurately. Diez et al. (2010) presented a quantitative uncertainty method for the ship design process by applying the Bayes theory. The conventional multidisciplinary design optimization (MDO) model and the MDO model based on robust design were established to address fin keel optimization. Lee et al. (2016) used the Kriging surrogate model and the genetic algorithm to optimize the aerodynamic performance of the wing sails. The shape of the wing sails and the working conditions were selected as optimization objectives. The results showed that the thrust performance of the optimal design was improved by 14–22% at all wind angles.

As discussed above, a great deal of research has been carried out on geometric hull reconstruction, hydrodynamic performance prediction, optimization algorithms, and surrogate models. Although the CFD method can produce more accurate prediction values and better capture flow field detail, the time cost is much larger than that of the potential flow method. Constructing a surrogate model with sufficient accuracy using as few samples as possible has yet to be studied. Support vector