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Hull form design optimization of twin-skeg fishing vessel for minimum resistance based on surrogate model

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ABSTRACT

Twin-skeg ship has better hydrodynamic performances than regular ship, however, it is still difficult to obtain an accurate relationship between skeg design and overall hydrodynamic performances. Resistance optimization is the major concern of developing twin-skeg ship. This paper proposes a combined approach for hull form design optimization of twin-skeg ship by using computational fluid dynamics (CFD) calculation and surrogate model. Main design parameters of skeg geometry and arrangement could be determined from the design domain by using the proposed method. Parametric modeling technology is adopted for performing design evaluations in an automatic manner with different design parameter combinations. A twin-skeg fishing vessel is selected as research object. In the proposed method, the sample set for constructing surrogate models is generated by using Optimal Latin Hypercube Sampling (OLHS) method, the corresponding responses are calculated through CFD simulations, and then the surrogate models are constructed by using Kriging modeling method, which represent the mathematical relationship between input design variables (skeg shape design variables) and output objective functions (resistance values under four different working conditions). The functional analysis of variance (ANOVA) is performed to investigate how much influence the design variables have on the objective functions. Finally, a multi-objective evolutionary algorithm (NSGA-II) is used to obtain the optimal solution, which shows 5.4% average decrease in the total resistance than the original design. The CFD calculation results of the optimal solution show that the proposed method can achieve minimum resistance design with high accuracy and low time cost.

1. Introduction

Generally, the draft of fishing vessel is usually restricted due to the shallow water of fishing port, which means the ratio of breadth to draft should be high to obtain enough capacity and get better maneuverability. And fishing vessel also is a kind of medium high-speed ship with high fuel consumption. To lower the fuel consumption for good energy saving and CO_2 emission reduction, it is necessary to design a fishing vessel type suitable for entering shallow water fishing ports and carrying out tasks in the distant sea with good resistance performance. Twin-skeg hull form is considered as one of the green ship solutions by Swedish State Shipbuilding Experimental Tank (SSPA) for ships with low ratio of length to breadth, high ratio of breadth to draft, restricted draft or heavy loaded propellers [1,2]. Currently, twin-skeg hull form is mainly used in large ships such as LNG carriers and container ships, which can benefit from irreplaceable advantages:

1.1. Good resistance performance

The skeg can be considered as slender body which has excellent resistance performance. In the twin-skeg hull form, the longitudinal gradient of stern is small so that the boundary layer separation can be controlled and the viscous pressure resistance can be reduced. The central tunnel formed between the two skegs is smooth so that the run body can be shortened, the maximum transverse section can move backwards 10%–15% ship length, and then the wave resistance is lower. Usually the total resistance of twin-skeg ship is less than conventional twin-screw ship, even less than some single-screw ship sometimes.

1.2. High propulsion efficiency

It can be proved by model test and numerical simulation that with limited draught, the screw propulsion efficiency of twin-skeg twin-screw ship is higher than that of conventional single-screw ship. That is because in twin-screw ship, the load of each propeller is reduced, which

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is good for improving the open-water efficiency. And twin-skeg twin-screw ship can make full use of the wake field, which can enhance the hull efficiency by circumference wake.

1.3. Good usability

The smaller propeller of twin-skeg twin-screw ship can achieve better cavitation and vibration performance. And the configuration of twin-screw twin-rudder can also improve maneuverability, safety and seakeeping performance.

Recent researches on twin-skeg ship hull form are mainly based on CFD numerical simulations. Sakamoto et al. conducted simulations of resistance and self-propulsion of a twin-skeg container ship for the selection of the optimal location of propeller with electronic propulsion system [1]. But the target of their research is not the optimization of the shape of skeg. Kim et al. presented a study on optimization of main dimensions and hull parameters of a twin-skeg LNG carrier based on the SSPA's parametric studies, CFD calculations and model tests, and achieved 13% reduction in fuel consumption comparing to a single-screw design [2]. Their study is on the basis of abundant model test data of SSPA, which is of great significance. However, when there is no test data or lack of test conditions, a new approach is needed for the optimization of the skeg form. Park et al. established an assess standard for the propulsion efficiency of twin-skeg ship according to the characteristics study of its stern flow [3]. But only vertical inclination angle and the distance between the two skegs, were used to express the skeg shape and geometry arrangement. Chen et al. constructed a fully parameterized model of a 10000TEU twin-skeg container ship and obtained 8.6% reduction in the total resistance by optimization of hydrodynamic performance [4]. In their study, vertical inclination angle and distance between skegs were also used in the optimization process, which cannot fully express the geometry features of the skegs. To investigate the influence of skeg shape and geometry arrangement on the total resistance, the design and optimization parameters should fully express the skeg shape and geometry arrangement and therefore should include vertical inclination angle, horizontal distance, length of the skeg slope, starting position and the fullness of the skeg.

It is well accepted that carrying out the research on the influence of skeg shape and geometry arrangement on the total resistance of twin-skeg ship is necessary. In this paper, a twin-skeg fishing vessel is selected for minimizing the total resistance R_T by optimization of skeg parameters to get lower power and lower fuel consumption. The optimization of stern shape and geometry arrangement is based on CFD calculations. To estimate the effective power curve, four different speeds are selected in the resistance calculation to assess the comprehensive resistance performance of one specified hull form design. However, the numerical simulations between optimization iterations are very time-consuming and impractical for this complex engineering problem. To alleviate the computational burden of the CFD calculations, Kriging modeling method is introduced in this study to substitute the true responses by four surrogate models for its accuracy and robustness with small data sets [5]. Based on the accuracy validation of surrogate models, a multi-objective optimization algorithm is introduced to search for the optimal shape design solution with the best estimation of resistance performance.

The Kriging modeling method, which is named after the South African geological engineer Krige DG, is mainly used for the deterministic optimization problems by predicting the value of unknown point using stochastic processes [6–8], and it is the best choice to approximate highly nonlinear response functions when the number of variable dimensions is moderate [5]. To be noted that the reason why the study is a deterministic optimization problem is that unlike actual physical experiments, the results of CFD calculations stay the same when repeating the calculation without any random error. Other relevant works on Kriging modeling study, such as multiple-fidelity sequential Kriging optimization (MFSKO) which use multiple-fidelity data and select the

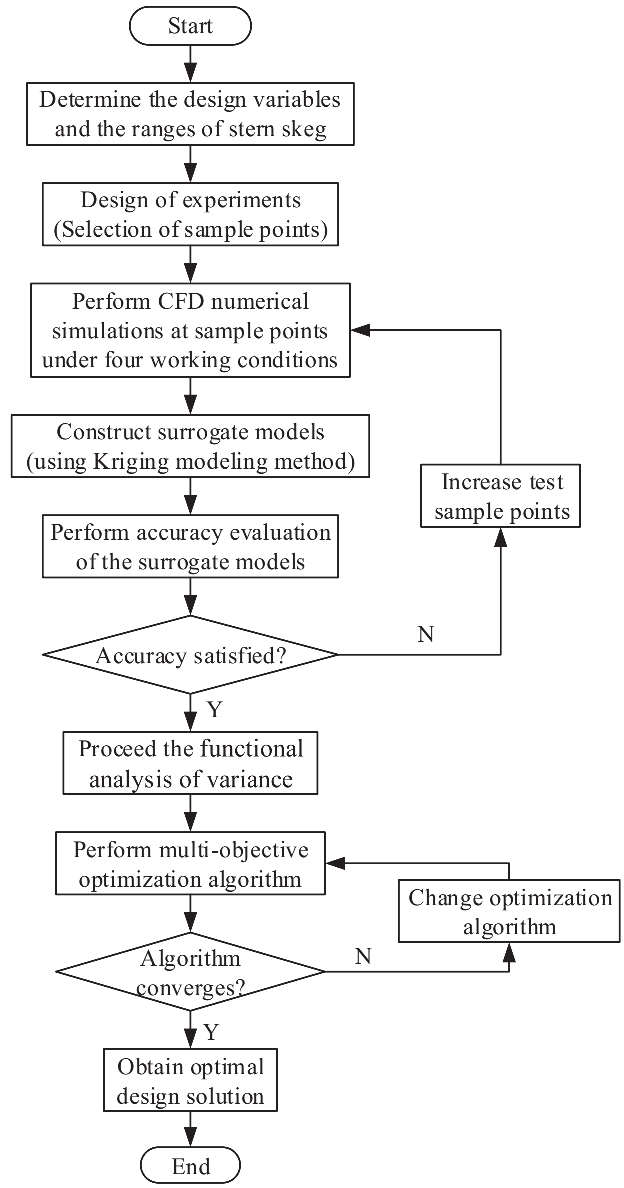

Fig. 1. The optimization procedure of the skeg shape and geometry arrangement.

location and fidelity level of the next evaluation by maximizing an augmented expected improvement function [9]. Meanwhile, Martin carried out the study on the parameters of Kriging model [10]. Furthermore, Kleijnen presented a detailed review of Kriging modeling method [11]. Kriging modeling method has been widely applied to engineering design optimization problems since Sacks et al. introduced it into structural reliability problems [12]. Kriging modeling method has also been actively used to aircraft and aerospace field. Jeong et al. combined Kriging modeling method and genetic algorithm (GA) to a 2-D airfoil design problem to optimize the lift-to-drag ratio [8]. Laurenceau and Sagaut first compared the global accuracy of different surrogate modeling strategies while the technique of sampling method varies, and verified the analysis by optimizing the shape of a transonic airfoil [13]. In the automotive field, Lee and Kang, Chen et al. and Gao et al. conducted their researches on Kriging-based optimization of automotive door's structure, ride comfort and crashworthiness respectively [14–16].

The overall flowchart of the optimization process is presented in Fig. 1. The rest of this paper is organized as follows. In Section 2, after a parameter study on the skeg of a twin-skeg fishing vessel, design of