

MULTI-OBJECTIVE OPTIMIZATION FOR A SURFACE COMBATANT USING NEUMANN-MICHELL THEORY AND APPROXIMATION MODEL

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ABSTRACT:

Hydrodynamic optimization of hull forms has drawn attention of both academia and industry during the development of shipbuilding industry and shipping business. An efficient potential flow theory based design optimization tool OPTShip-SJTU for ship hull form is presented in this paper, which is composed of three function modules: hull form deformation module, hydrodynamic performance prediction module and optimization module. Free-Form Deformation (FFD) method and Radial Basis Function (RBF) method are employed to modify the ship hull in global and local respectively. In order to reduce the cost of the optimization, which is always a challenging problem, a new hydrodynamic prediction tool based on Neumann-Michell (NM) theory and the approximation model is adopted. The high efficiency is illustrated by the application of OPTShip-SJTU to a surface combatant DTMB 5415. Wave resistance coefficients at three design speeds are minimized and a Pareto front of solutions is obtained. The optimal hulls are verified and analyzed by NM theory and a RANS-based CFD solver naoe-FOAM-SJTU. Numerical results confirm the availability and reliability of the OPTShip-SJTU.

INTRODUCTION

In the recent decades, with the development of shipbuilding industry and shipping business, hydrodynamic optimization of hull forms has drawn attention of both academia and industry. Especially for the container ship, its economic efficiency depends mainly on the hydrodynamic performances. In order to obtain a hull form with best hydrodynamic performances, the design engineers have constructed some approaches with different hydrodynamic analysis methods, geometrical modification techniques and optimization algorithms. However, Due to the complexity of ship hydrodynamics and the huge number of evaluations of objective functions in optimization, the cost of ship hull optimization is quite time consuming. In order to solve this problem, the combination of a new efficient hydrodynamic analysis method and approximation model is adopted as a feasible scheme for the ship hull optimization.

Prediction of hydrodynamic performance for a ship is always a challenging part during the optimization process. The hydrodynamic analysis method should be not only efficient, for a variety of hull forms to be evaluated, but also robust, which means the distinction among hulls with a little modification could be recognized. In recent years, these methods including potential flow theory and RANS equation method have been employed for the use of hydrodynamic analysis. Suzuki [1] used potential flow solver based on Hess and Smith method [2] and Rankine source method [3] to evaluate the energy of secondary flow for a tanker hull form optimization. Baoji [4] obtained the optimized hull form with minimum wave-making based on Rankine source method combined with optimization methods. Currently, a new efficient potential theory, named Neumann-Michell (NM) theory [5], is

integrated in the optimization process to evaluate the objective functions. The computation of the steady flow around a moving ship based on NM theory is efficient and robust due to the succinctness of this theory. Kim [6] has also adopted similar potential theory in optimizing for ship hull form.

Geometry modification is also an important module in ship hull optimization process. An appropriate and effective technique is sought by several attempts, which have tested methods based on different theories. Kim [6] modified the Wigley hull form basing on parametric hull representation and NURBS surface, and Peri [7] utilized Bézier Patch to complete the modification of hull geometry, while the FFD method was employed by Tahara [8] to modify the shape of Delft Catamaran. For sake of conciseness and flexibility, two ideal approaches including RBF method and FFD method are utilized in present study. FFD method is introduced to modify the ship hull globally, and RBF method is adopted to modify the bulbous bow. Both two methods are proven to be flexible and reasonable.

Algorithm is also a considerable factor in the time cost of optimization process and sometimes determines the “quality” of optimized solutions. Various algorithms have been investigated and compared with each other [9-12]. Although the local optimization schemes are time-saving, they are easily trapped in the local optimum when solving the hull form design problems. For the uncertainty of real sea environment and a container ship usually advancing in different speeds, a multi-objective optimization scheme should be adopted, and then the optimal ship hulls will have a consistent drag reduction in a large range of speed compared with the original one. Therefore, the multi-objective genetic algorithm (NSGA-II) has been employed to obtain Pareto front.

In this paper, the hull form of surface combatant ship DTMB 5415 is optimized for objective functions of wave drag in three speeds within an in-house hydrodynamic optimization tool OPTShip-SJTU. Both local and global hull transformation methods are used to modify the sonar dome bow and the hull shape. A series of Pareto-optimal solutions are obtained and four cases are selected to be verified and analyzed by a RANS-based CFD solver naoe-FOAM-SJTU, which is developed based on OpenFOAM and has been validated in previous work [13]. According to the comparison with prediction from RANS-based CFD solver, the Neumann-Michell theory is proven to be efficient and reliable. Besides, the optimization scheme combined with approximation model seems an ideal choice for ship design and amelioration.

HYDRODYNAMIC PERFORMANCE PRIDITION

Neumann-Michell theory, proposed by Noblesse [5], is efficient and accurate in predicting wave resistance. It is an important attribute for a practical hydrodynamic analysis module in the hull form optimization process. The NM theory is presented as below.

Brief introduction of Neumann-Michell Theory

When a ship steadily advances at constant speed along a straight path in calm water of effectively infinite depth and lateral extent, the wave drag related to the waves generated by the advancing ship hull is of considerable practical importance because drag is a critical and dominant hydrodynamic factor for ship design. The Neumann-Michell (NM) theory is an efficient potential flow theory used to predict the ship waves. This theory is the modification of Neumann-Kelvin theory and based on a consistent linear flow model. The main difference

between the two theories is that the line integral around the ship waterline that occurs in the classical NK boundary-integral flow representation is eliminated in the NM theory, so the NM theory expresses the flow about a steadily advancing ship hull in terms of a surface integral over the ship hull surface. The detail of this theory is given in reference [5].

Validation of the Neumann-Michell theory

The validation study for NM theory is carried out before the optimization. For DTMB Model 5415, the comparisons between experimental data and drag predictions given by NM theory (C_w), ITTC formula (C_f), and naoe-FOAM-SJTU are shown in Fig. 1.

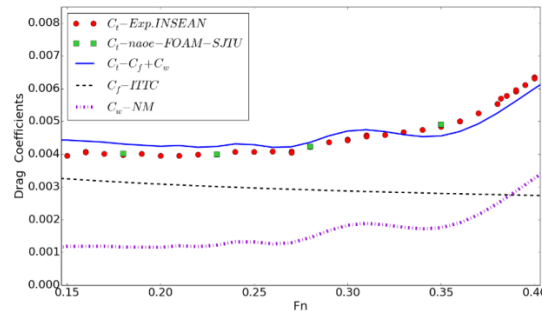


Fig. 1 Comparison of drag coefficients for the DTMB Model 5415

The error precision between naoe-FOAM-SJTU and the experimental data is no more than 2%, and the error precision between NM theory and the experimental data is no more than 9%. Although the precision of NM theory is not as accurate as that of naoe-FOAM-SJTU, the prediction of NM theory can provide correct relative comparisons of the drags of alternative solutions in Fig.1. Besides, NM theory requires only a few minutes using a PC to obtain the prediction while naoe-FOAM-SJTU requires several hours or even days, so the efficiency of NM theory is higher than naoe-FOAM-SJTU, which is much more critical to optimization at early stage. Therefore, this practical prediction method based on NM theory is quite qualified for the optimization work.

MODIFICATION METHODOLOGY OF SHIP HULL

It is always an essential issue to find an appropriate and effective surface modification method in ship hull optimization process. On the one hand, these techniques should modify hull forms efficiently and ensure the rationality of the new hull, on the other hand, the number of variables involved in these methods should keep as low as possible—too much design variables will increase the complexity of the problem and lead to vast computational cost.

In this study, two efficient approaches are employed to deform the ship hull both locally and globally. The first one is based on the trivariate Bernstein polynomials [14], and the other one is derived from an interpolation technique using a radial basis function [15].

Free Form Deformation (FFD)

In this paper, FFD (Free Form Deformation) technique, proposed by Sederberg and Parry [15] and based on trivariate Bernstein polynomials, is utilized to perform the deformation of solid geometric models in a free-form manner. In this method, the objects to be deformed are embedded into a plastic parallelepiped, and then these objects are deformed along with it. With this approach, the modification of hull form is defined and controlled by using a few

control nodes that are used as design variables by optimizer. This method was also adopted in reference [16, 17]. More details about the scheme can be found in reference [14].

In present study, FFD technique is utilized as a global modification tool for the ship profile. Surface near the ship bow is embedded into a parallelepiped on which the control points are imposed.

An application of FFD approach to modify a ship bow was shown in Fig. 2. The surface to be deformed is wrapped by a parallelepiped, and both of the movable control points (purple spheres) and fixed control points (yellow spheres) are shown. Significant differences due to the movements of control points can be observed between the two bow shapes shown in Fig. 2(a) and Fig. 2(b).

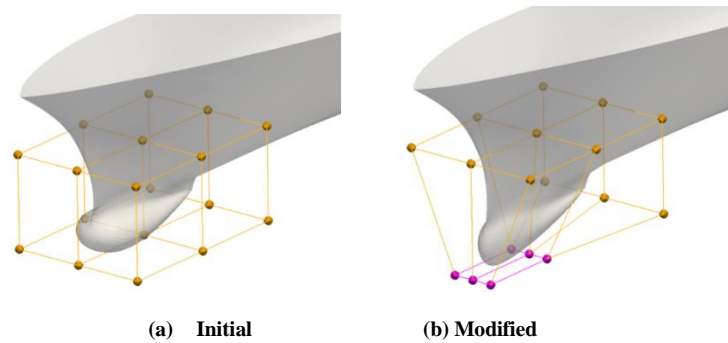


Fig. 2 An application of FFD method to modify the ship bow

Radial Basis Function (RBF)

Radial Basis Function is a scalar function symmetric along the radial direction. Boer [15] first applied it into a dynamic mesh method. In this study, the local modification of ship hull form is accomplished by RBF method.

The interpolation function $s(\mathbf{X})$, which describes the displacement of each point on the hull surface, e.g., node if the hull surface is represented by a discrete triangulation, or in the entire domain, can be approximated by the sum of the radial basis functions and a polynomial as follows:

$$s(\mathbf{X}) = \sum_{j=1}^N \lambda_j \phi(\|\mathbf{X} - \mathbf{X}_j\|) + p(\mathbf{X}) \quad (1)$$

where $\mathbf{X}_j = (x_j, y_j, z_j)$ is the center of the radial basis function, at which the interpolation function, $s(\mathbf{X})$, is known, $p(\mathbf{X})$ a polynomial, N the number of control nodes (centers) and ϕ a given radial basis function with respect to the Euclidean distance $\|\mathbf{X}\|$. In this paper, the radial basis function ϕ in (1) is defined in terms of *Wedndland's C2* function as follow:

$$\phi(\|X\|) = \begin{cases} (1 - \|X\|)^4 (4\|X\| + 1) & 0 \leq \|X\| \leq 1 \\ 0 & \|X\| > 1 \end{cases} \quad (2)$$

More details about the scheme can be found in reference [15].

By then, displacement of all nodes are calculated by (1) with the solved coefficients. The new hull form is obtained. In the application in the ship hull modification, all nodes on the ship hull surface are divided into three types:

- (a) Fixed control nodes: the nodes used to keep the hull surface near them unchanged, always on the characteristic lines, such as designed waterline, longitudinal line and midship line.
- (b) Movable control nodes: the nodes used as design variables in the optimization procedure, always on the special position which deserves attention of designers.
- (c) Free nodes: the nodes moving with movable control nodes.

APPROXIMATION MODEL IN OPTIMIZATION

Experimental design method

Approximation model is an important way to reduce the computational cost for optimization process. However, as the increasing number of design parameters and constraints, the approximation model becomes more complicated, and the computational cost of surrogate construction and numerical simulation becomes unaffordable. How to obtain an accurate approximation model with less numerical simulation samples is the key issue for optimization with surrogate model.

The design of experiment (DOE) is the best way to solve this problem, it can reduce the simulation iterations and obtain high accurate approximation model. Among DOE methods, the most fundamental one is the factorial design [18]. The full factorial design contains all combinations of all design parameters in every level. The number of required simulation times grows exponentially with increasing of numbers of the design parameters and the levels. To avoid the increasing computational cost, many DOE methods are proposed.

Optimal Latin hypercube design [19] is a modified Latin Hypercube design, in which the combination of factor levels for each factor is optimized, rather than randomly uniformly divided (the same number of divisions for all factors). The Optimal Latin hypercube design is illustrated in Fig.3 for a configuration with two factors and nine design points. Fig.4 (a) shows the standard orthogonal array and Fig.3 (b) shows the Random Latin hypercube design. The Optimal Latin hypercube is shown in Fig.3 (c), which cover nine levels of each design parameters. And as we can see, the design points of Optimal Latin hypercube are spread evenly within the design space.

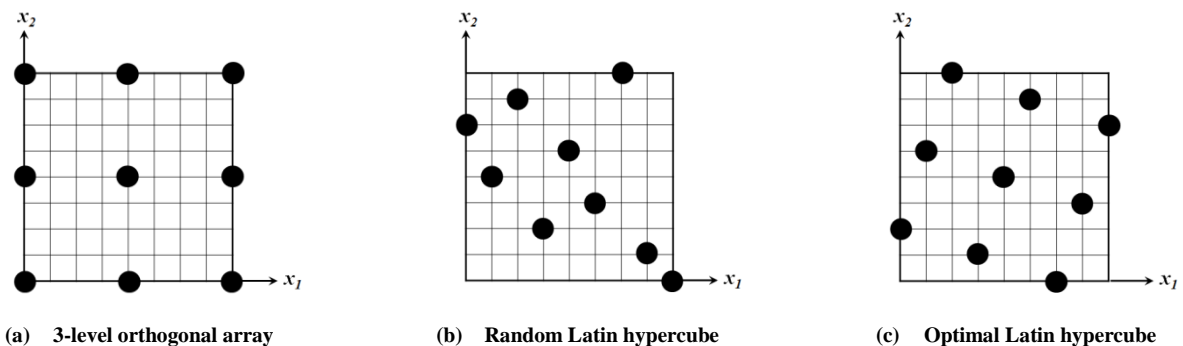


Fig. 3 Three types of experimental design method

In this paper, Optimal Latin hypercube design is used to generate the sample points of approximation model, which could ensure the accuracy of the approximation model.

Mathematics of Kriging

Kriging model [20] is developed from best linear unbiased prediction method, which has its origins in mining and geostatistical applications involving spatially and temporally correlated data. Kriging model combines a global model and local components:

$$y(x) = f(x) + z(x) \quad (3)$$

Where $f(x)$ is the global model similar to a polynomial response surface model, and local component $z(x)$ is a measure of the deviations from the global model. With $f(x)$ and $z(x)$, the Kriging model can build the surrogate model between the input variables and output variables. More details about Kriging model can be found in reference [20].

OPTIMIZATION FORMULATION

Non-dominated sorting genetic algorithm

Non-dominated sorting genetic algorithms NSGA and NSGA-II are proposed by Srinivas and Deb *et al.* [21, 22]. They have been applied into many engineering optimization problems. In this paper, NSGA-II algorithm is adopted to drive the optimization procedure.

In this work, NSGA-II algorithm is employed to obtain Pareto solutions in the ship hull optimization. The crossover rate is 0.75 and the mutation rate is 0.10. The number of generation is selected to be 500 with each generation containing 400 individuals.

Optimization model of DTMB 5415

Multi-objective optimization problem in this paper is defined as:

$$\min f(x) = [f_1(x), f_2(x), f_3(x)] \quad (4)$$

where each objective function $f_i(x)$ demonstrates wave drag at each design speed ($Fr=0.20, 0.30, 0.40$).

The optimization variables are determined by the two hull modification methods. FFD method is employed to modify the geometry of ship hull globally, and three parallelepipeds shifting in different directions are illustrated in Fig.4. In terms of the local modification of bulbous bow of the ship, three nodes with different moving directions are chosen for the RBF method. The design constraints are listed in Table 1.

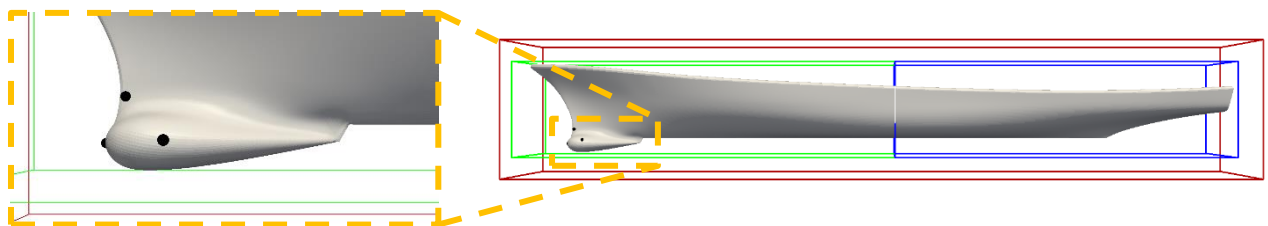


Fig. 4 Ship hull modification settings with RBF and FFD method.

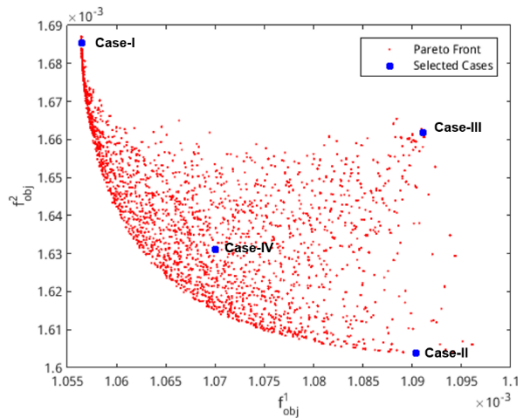
Table 1 Design Constraints

Geometric Constraints	Symbol	Value%Original
Length between perpendiculars	L_{pp}	0
Beam	B	0
Draft	T	0
Displacement	∇	1.0
Wetted area	S_{wet}	1.0

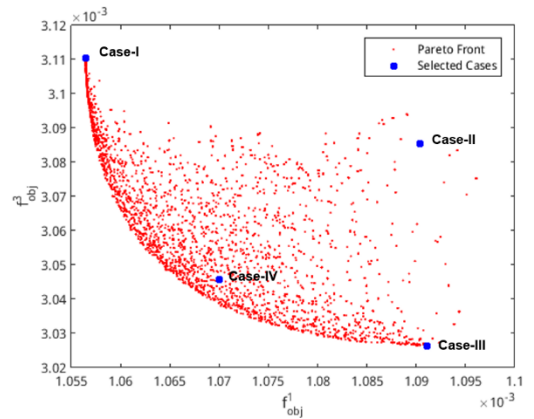
OPTIMIZATION RESULTS

Pareto Front and selected cases

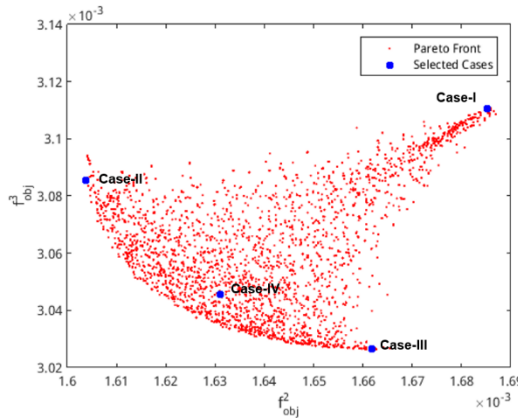
As shown in Fig. 5, more than five hundreds Pareto-optimal solutions have been found. Among them, three cases with minimum wave drag in each design speed and an eclectic case with wave drag reduction all in three speeds are chosen.



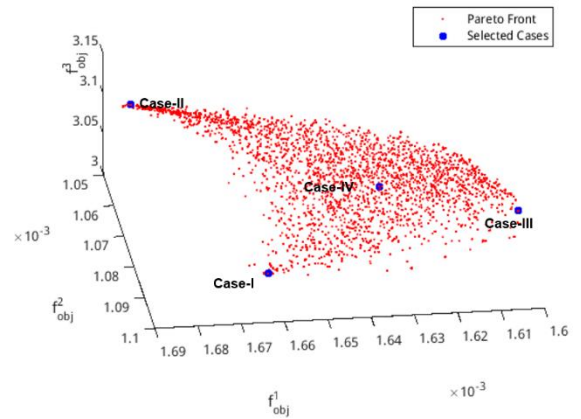
(a) Pareto front in f_{obj}^1 and f_{obj}^2



(b) Pareto front in f_{obj}^1 and f_{obj}^3



(c) Pareto front in f_{obj}^2 and f_{obj}^3



(d) Pareto front in f_{obj}^1 , f_{obj}^2 and f_{obj}^3

Fig. 5 Pareto front and selected cases in objective function space

Table 2 shows the comparison of performances between original ship hull and four selected cases, which include displacement, wetted area and three wave drags in each speed. The selected cases all have more than 5% reduction of each objective function. For the constrains of the ship hull, the displacement and wetted area of each selected cases have fewer than 0.15% change of original hull's.

Table 2 Comparison of performances between original ship hull and selected cases

	Original	Case-I	Case-II	Case-III	Case-IV
Displacement %Original	0	-0.14%	-0.07%	-0.13%	-0.07%
Wetted area %Original	0	-0.08%	-0.03%	-0.10%	-0.04%
f_{obj}^1 (%Original)	0.001169	0.001056(9.67%)	0.001091(6.67%)	0.001092(6.59%)	0.001070(8.47%)
f_{obj}^2 (%Original)	0.001851	0.001688(8.81%)	0.001603(13.4%)	0.001633(11.8%)	0.001631(11.8%)
f_{obj}^3 (%Original)	0.003305	0.003110(5.90%)	0.003086(6.63%)	0.003027(8.41%)	0.003045(7.87%)

Fig. 6 presents the comparison of ship hull form between original hull and optimal hulls. The sonar dome bow in each case has an obvious lifting in vertical direction. And the lift of case-II is the biggest. In Fig. 6(e), it can be seen that the sonar dome bow become larger than the original hull.

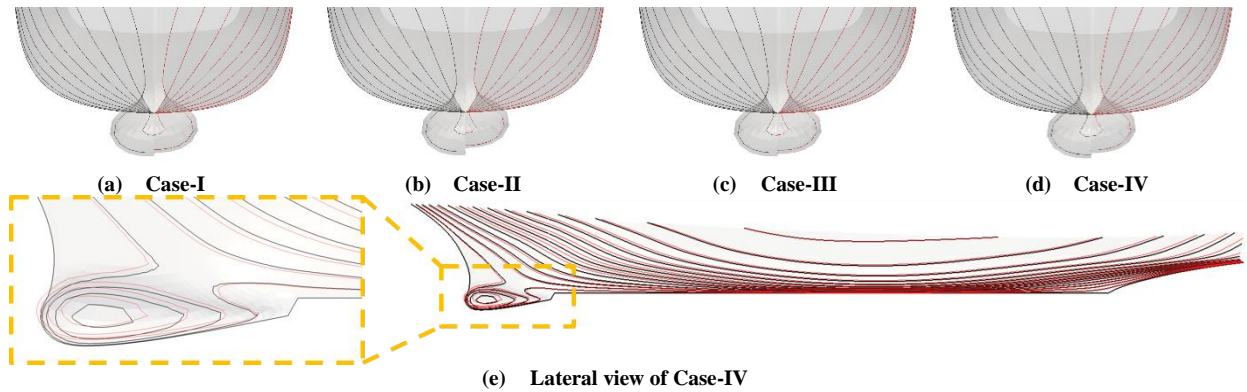


Fig. 6 Comparison of ship form lines between original hull (black line) and selected cases (red line)

Verification of case-IV with naoe-FOAM-SJTU

To further analyze the flow feature of optimal hulls, wave pattern for three speeds are predicted by naoe-FOAM-SJTU, which is shown in Fig. 7. It can be concluded that the wave around the stern of Case-IV is smaller than the original one, which results the wave drag reduction of ship hull directly.

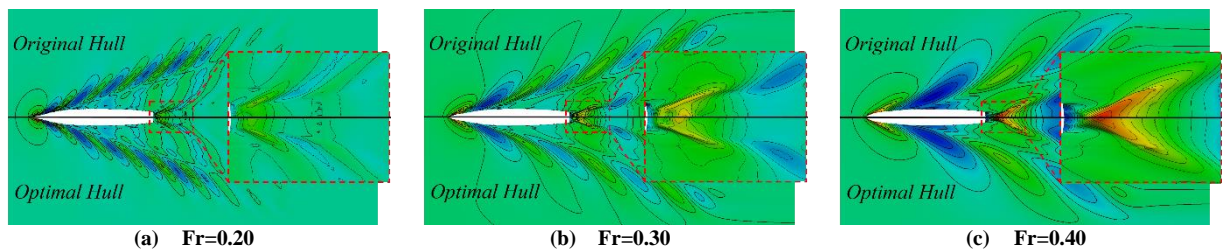


Fig. 7 Comparison of wave pattern between original hull and Case-IV predicted by naoe-FOAM-SJTU

CONCLUSIONS

1. DTMB 5415 is adopted as original hull form with the objective functions are the wave resistance coefficients in three different speeds by a numerical multi-objective optimization tool, OPTShip-SJTU.
2. During the optimization progress, optimal Latin Hypercube method is used to generate the experimental design matrix, Kriging model is used as the approximation model.

3. The use of Neumann-Michell theory as the prediction method of ship hydrodynamic performance is proved to be both efficient and effective, although the hydrodynamic performance is limited to the wave drag.
4. The combination of FFD method and RBF method has performed well both in particular region and whole form of the ship. The bulbous bow and the whole shape are modified by RBF and FFD methods.
5. Pareto front is successfully obtained after 2000,000 iterations of evaluation for objective functions. Four cases are selected from Pareto solutions, and Case-IV is verified by a RANS solver naoe-FOAM-SJTU. The Optimal results confirm the validity of the combination of the approximation method and NM theory in the application for ship hull form optimization.
6. Further work will focus on the extension of the performances evaluation including seakeeping, maneuvering and so on. And the efficiency and accuracy of approximation model need more attention so as to provide a better optimization tool with more disciplines.

ACKNOWLEDGMENTS

This work is supported by the National Natural Science Foundation of China (51379125, 51490675, 11432009, 51579145, 11272120), Chang Jiang Scholars Program (T2014099), Program for Professor of Special Appointment (Eastern Scholar) at Shanghai Institutions of Higher Learning (2013022), and Innovative Special Project of Numerical Tank of Ministry of Industry and Information Technology of China (2016-23/09), to which the authors are most grateful.

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