Multi-objective hydrodynamic optimization for ONR tumblehome ship

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ABSTRACT: A numerical multi-objective optimization procedure is proposed here to describe the development and application of a practical hydrodynamic optimization tool, OPTShip-SJTU[14,15]. Three components including hull form modification module, hydrodynamic performance evaluation module and optimization module consist of this tool. In this paper, the free-form deformation (FFD) method are utilized as parametric hull surface modification techniques to generate a series of realistic hull forms subjected to some design constraints during the optimization process. In performance evaluation module, Neumann-Michell (NM) theory is employed here to predict the wave-making drag at low computational cost. Additionally, Kriging models are established based on OLHS samples as surrogates for optimization process, and a multi-objective genetic algorithm named NSGA-Ⅱhas been employed to provide pareto-optimal front. ONR Tumblehome model 5613 is taken as preliminary design, and the two objective functions have been chosen as the wave resistance at two speeds (*Fr* = 0.2, 0.3), Eventually, the pareto optimal set which provides over 4000 optimal hull forms is obtained by using NSGA-Ⅱalgorithm, and three of them are chosen for further analysis. The numerical optimization results are analyzed, and the availability of the OPTShip-SJTU is confirmed by this application.

KEY WORDS: OPTShip-SJTU, Multi objective optimization, NSGA-Ⅱalgorithm, Neumann-Michell theory, wave drag

INTRODUCTION

In the recent decades, hydrodynamic optimization of hull forms has gained extensive attention of both industrial and academic due to the considerable benefits associated with it. Hydrodynamic performances are enhanced through the optimization process, accordingly, the optimal ship will become more energy-saving and competitive. Previously, in order to obtain a good hull form, ship designers had to try a large of combinations of design variables to search for the optimal solution through experimental tests, however, this method is considered to be too expensive, inefficient and less accurate. With the development of computer techniques, ship design engineers have constructed various approaches with different hydrodynamic analysis methods, geometrical deformation techniques and optimization algorithms, these methods have been integrated into some ship hydrodynamic optimization tools, and they have been presented in a huge body of literature.

As for geometry modification, several attempts have been made to deal with this problem. Kim [1] modified the Wigley hull form basing on parametric hull representation and NURBS surface, and Tahara et al. [2] utilized FFD method to complete the modification of hull geometry. Also, hydrodynamic performance prediction is a crucial part for optimization, Baoji et al. [3] obtained the optimized hull form with minimum wave-making based on Ranking source method. Tahara et al. [2] utilized two free-surface RANS solvers which named CFDSHIP-Iowa and MGShip to predict the total resistances in different SBD approaches. With regard to optimization module, various algorithm had been applied to obtain final results, and surrogate models were established to decreases the optimization difficulty and computational cost. More detail information could be found in references [5-7].

In this paper, the ONR Tumblehome model 5613, a preliminary design of a modern surface combatant which is publically accessible for fundamental research, is adopted as the initial hull form, and the three objective functions have been chosen as the wave resistance at two speeds (*Fr* = 0.2, 0.3). The geometry of hull form is modified globally and locally by FFD method. Specifically, the local surface around the ship bow is modified for drag reduction, and three design variables are derived from it. Additionally, for maintaining the functionalities of ship, some geometric constraints are imposed on the design variables, displacement and wetted surface area. 50 samples are generated by OLHS method and the resistance coefficients are estimated with NM theory. Kriging model is established based on the samples and is used to provide the estimates during the optimization process. Eventually, the pareto optimal set which provides over 4000 optimal hull forms is obtained by using NSGA-Ⅱ algorithm, and three of the pareto solutions are chosen for analysis and validation. These numerical results confirm the availability and reliability of the multi-objective optimization tool.

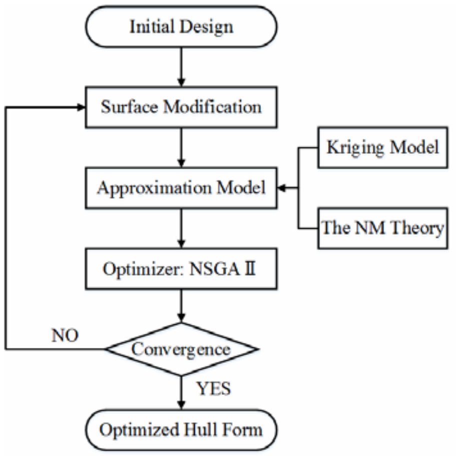
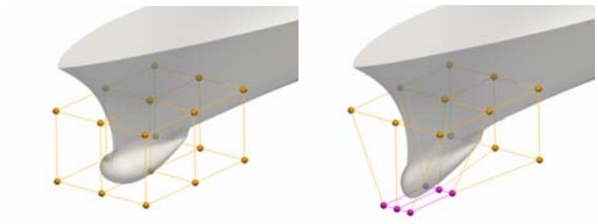


Fig. 1 The flow chart of the iterative optimization process

HULL FORM DEFORMATION

Successful hull form deformation requires an appropriate and effective surface modification method. The hull surface should be modified efficiently and flexibly, while the number of variables involved should keep as low as possible. In this paper, FFD technique, proposed by Sederberg and Parry [8] and based on trivariate Bernstein polynomials, is utilized to perform the deformation of solid geometric models in a free-form manner. The surfaces to be deformed are embedded into a plastic parallelepiped. The modification of hull form is defined and controlled by a few movable control nodes. The deformation is performed by moving the control nodes $Q_{i,j,k}$ from their original positions, and the deformed position X_{ffd} of any point X (s, t, u) can be obtained as following:

$$X_{ffd} = \sum_{i=0}^{l}\sum_{j=0}^{m}\sum_{k=0}^{n} B_{i,j}(s)B_{j,m}(t)B_{k,n}(u)Q'_{i,j,k} \tag{1}$$



(a) Initial (b) Modified

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

An application of FFD approach is presented in Fig. 2. The ship bow surface is wrapped by a parallelepiped, and changed with the movements of control points. Movable control points are colored with purple while the fixed control points are colored with yellow.

PERFORMANCE EVALUATION

Lots of hull forms will be generated and evaluated during the optimization process, accordingly, it is important to choose a practical CFD analytical tool to predict corresponding performance to every hull form. The optimizer is guided by the evaluating results toward the improved solutions, so, both accuracy and efficiency are crucial for this tool. In this study, a flow solver based on a modified theory — called Neumann-Michell (NM) theory [9] is employed to evaluate the drag of a ship hull. 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, then the NM theory expresses the flow about a steadily advancing ship hull in terms of a surface integral over the ship hull surface. It has been proved to be a practical calculation with sufficient accuracy and is well suited for early-stage ship design and optimization [10] due to the simplicity and fast computation. The Neumann-Michell potential representation is offered as following:

$$\tilde{\phi} = \tilde{\phi}^W + \tilde{\phi}^L = \tilde{\phi}_H + \tilde{\psi}^W + \tilde{\psi}^L \tag{2}$$

where the three components are defined as :

$$\begin{aligned} \tilde{\phi}_H &\equiv \int_{\Sigma^H} G\, n^x \, \mathrm{d}a - \int_{\Sigma^F} G \pi^{\phi} \, \mathrm{d}x\mathrm{d}y \\ \tilde{\psi}^L &\equiv -\int_{\Sigma^H} \phi \mathbf{n} \cdot \nabla L \mathrm{d}a + F^2 \int_{\Gamma} \frac{\phi L_x n^x \mathrm{d}l}{\sqrt{(n^x)^2 + (n^y)^2}} \\ \tilde{\psi}^W &= \int_{\Sigma^H} (\phi_{t'} \mathbf{d}_* + \phi_{d'} \mathbf{t}_*) \cdot \mathbf{W} \mathrm{d}a \end{aligned} \tag{3}$$

Then the $\tilde{\psi}^L$ term is neglected for practicability of the NM theory. The simplified NM representation of the flow potential is expressed as:

$$\tilde{\phi} \approx \tilde{\phi}_H + \tilde{\psi}^W \equiv \tilde{\phi}_H^L + \tilde{\phi}_H^W + \tilde{\psi}^W \equiv \tilde{\phi}_H^L + \tilde{\phi}^W \tag{4}$$

A validation of NM is carried out before optimization. Wigley hull is chosen as the benchmark hull, and the sum of C_f given by ITTC friction formula and C_w predicted by NM is regarded as the total drag C_t. The comparisons of experimental data and analytical results are shown in Fig. 3. The results prove that the NM theory is quite qualified for the optimization work.

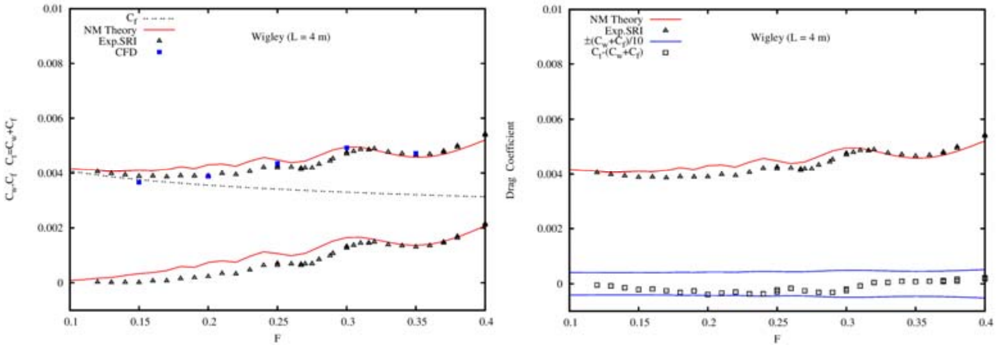


Fig. 3 Comparison of drag coefficients for wigley hull

HULL FORM DEFORMATION

The design of experiment (DOE) methods is the best way to obtain appropriate CFD simulation samples. Optimal Latin hypercube design [11] is applied here to guarantees the accuracy of the approximation model. Kriging model[12] is developed from best linear unbiased prediction method, which has its origins in mining and geostatistical applications involving spatially and temporally correlated data. In order to reduce the computational cost for optimization based on CFD method, this approximation model has been integrated into OPTShip-SJTU[14,15]. With regards to optimization algorithm, NSGA-II, proposed by Srinivas and Deb [13], is adopted to drive the optimization procedure. After 60000 iterations of 300 generations and 200 individuals, the Pareto-optimal solutions are obtained finally.

DEFINITION OF OPTIMIZITION PROBLEM

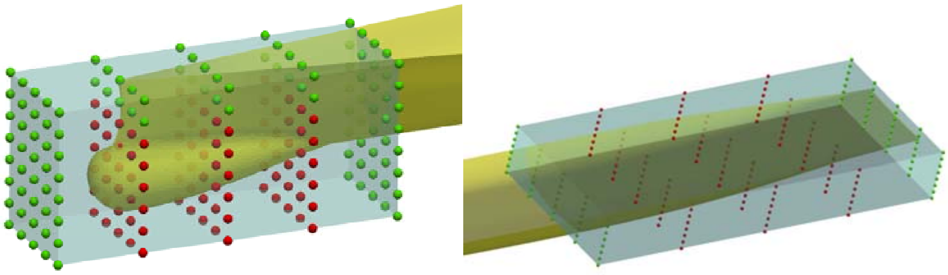
The initial hull form is chosen as the ONR Tumblehome model 5613 which is a preliminary design of a modern surface combatant and is publically accessible for fundamental research. The geometry of the initial model is presented in Fig.4 and the principal dimensions of ONR Tumblehome is listed in table 1.

Table 1 The principal dimensions of ONR Tumblehome model 5613

Principal Dimensions	full-scale ship	ship model
Length of waterlines L_{wl}/m	154.0	3.147
Breadth moulded B/m	18.78	0.384
Depth moulded D/m	14.5	0.266
Draught T/m	5.494	0.112
Displacement Δ	8507ton	72.6kg

Fig. 4 The geometry of ONR Tumblehome model 5613

In this paper, the geometry of ship hull surface is represented with unstructured meshes. FFD method is utilized to modify the nodes on the hull surface globally and locally. Two parallelepipeds containing 200 control points are established here and reported in Fig. 5. The former one is used to modify the ship bow and the latter one is utilized to deform the aft-body. The movable control points are colored with red and the fixed points are colored with green. When the red control nodes are moved to the new positions, the nodes on hull surface wrapped by the parallelepipeds can be moved according to the representation (1), then new hull surface will be obtained. Three design variables x1, y1, z1 can be derived from Fig. 5(a), and they determinate the displacements of movable control nodes (red) in the x, y, z directions respectively. Similarly, the fourth variable x2 can be derived from Fig. 5(b). It is notable that these red control nodes are move towards unity, and the amount of movement along x direction is determined by variable x2.



(a) Parallelepiped and control nodes near the bow (b) Parallelepiped and control nodes in aft-body
Fig. 5 Parallelepiped and control nodes using in FFD method

A summary of these four design variables is reported in Table. 2. The first three ones modify the ship bow locally while the last one deform the aft body of hull surface globally, and they are applied to the hull at the same time.

Table 2 Summary of design variables

Design Variables	Range	Note
x1	[-0.010, 0.010]	Displacement in x direction in Fig. 5 (a)
y1	[-0.005, 0.006]	Displacement in y direction in Fig. 5 (a)
z1	[-0.006, 0.006]	Displacement in z direction in Fig. 5 (a)
x2	[-0.03, 0.03]	Displacement in x direction in Fig. 5 (b)

For obtaining practical optimal solutions, the two objective functions have been chosen as the wave resistance at two speeds (Fr = 0.2, 0.3).

$$\textbf{Min} \ f([\mathrm{x}]) = \{f_{obj}^{1}, f_{obj}^{2}\} \tag{5}$$

$$f_{obj}^{1} = C_{w1}, \qquad at \ \ Fr = 0.20 \tag{6}$$

$$f_{obj}^{2} = C_{w2}, \qquad at \ \ Fr = 0.30 \tag{7}$$

Some geometric constraints should be considered to maintain the shape and characteristic of optimal ship consistent with the original one. In this paper, the main dimensions are fixed during the optimization process, and the variations of displacement and wetted area are restrained within 2%.

$$\text{s.t.} \ \ g_1 = {L_{pp}}^{opt} - {L_{pp}}^{ini} = 0 \tag{8}$$

$$g_2 = T^{opt} - T^{ini} = 0 \tag{9}$$

$$g_3 = B^{opt} - B^{ini} = 0 \tag{10}$$

$$g_4 = \left| \frac{\nabla^{opt} - \nabla^{ini}}{\nabla^{ini}} \right| \le 2\% \tag{11}$$

$$g_5 = \left| \frac{S_{wet}^{\ opt} - S_{wet}^{\ \ ini}}{S_{wet}^{\ \ ini}} \right| \le 2\% \tag{12}$$

RESULTS

The pareto optimal solutions are obtained through optimization process, and these results are presented in Fig. 6.

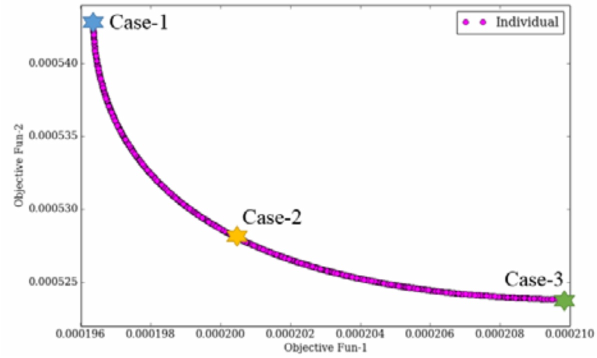


Fig. 6 Pareto front and selected cases in objective function space

Table 3 Summary of design variables

	Case-1	Case-2	Case-3
Var1	-0.00207	-0.00183	-0.00163
Var2	-0.00446	-0.00445	-0.00444
Var3	-0.00001	0.00011	0.00023
Var4	0.01146	0.01423	0.01660
Displacement%	-0.89%	-0.99%	-0.79%
Wetted area%	-1.60%	-1.85%	-1.31%

Table 4 Prediction and comparison of drag performance

	Fr=0.28			Fr=0.41		
	C_w ($\times10^{-3}$)	C_f ($\times10^{-3}$)	C_t ($\times10^{-3}$)	C_w ($\times10^{-3}$)	C_f ($\times10^{-3}$)	C_t ($\times10^{-3}$)
Origin	0.728	3.633	4.361	1.074	3.367	4.441
Case-1	0.304	3.633	3.937	0.641	3.367	4.008
improvement %			*9.71%*			*9.76%*
Case-2	0.310	3.633	3.943	0.639	3.367	4.006
improvement %			*9.58%*			*9.80%*
Case-3	0.318	3.633	3.951	0.618	3.367	3.985
improvement %			*9.39%*			*10.27%*

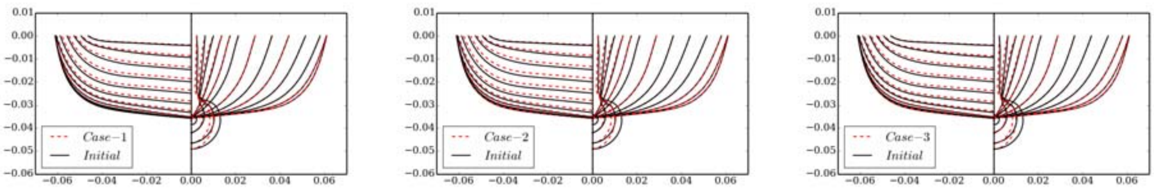


Fig. 7 Comparisons of body plans between the initial design and the optimal hull forms

Three cases, named Case-1, Case-2 and Case-3 are picked out from the pareto solution set and chosen for further analysis. They are illustrated in Fig. 6 and relatively large differences existing in the values of objective functions can be detected among these cases. The values of design variables corresponding to the three cases are listed in Table. 2, and the variations of displacement and wetted area are within 2%, just as expected in the beginning of optimization. The optimization results are provided by the optimization algorithm, and the NM theory is employed to investigate drag performance of the three cases. The predictions and comparisons are presented in Table 3. It can be known from the table that both of the resistance performances at *Fr* =0.2, 0.3 are improved more than 9%, and the best solution will be chosen with more consideration to achieve a balance between the two objective functions. The comparisons of body plans between the initial design and the optimal hull forms are illustrated in Fig. 7. Although there are slightly geometrical differences exiting among these cases, some common features can be detected from the body plans. The widths of bulbous bows significantly decrease while the aft bodies tend to be more slender. Finally, the comparisons of free surfaces between initial and optimal designs are shown in Fig. 8. It can be observed that optimal ones have lower wave amplitudes.

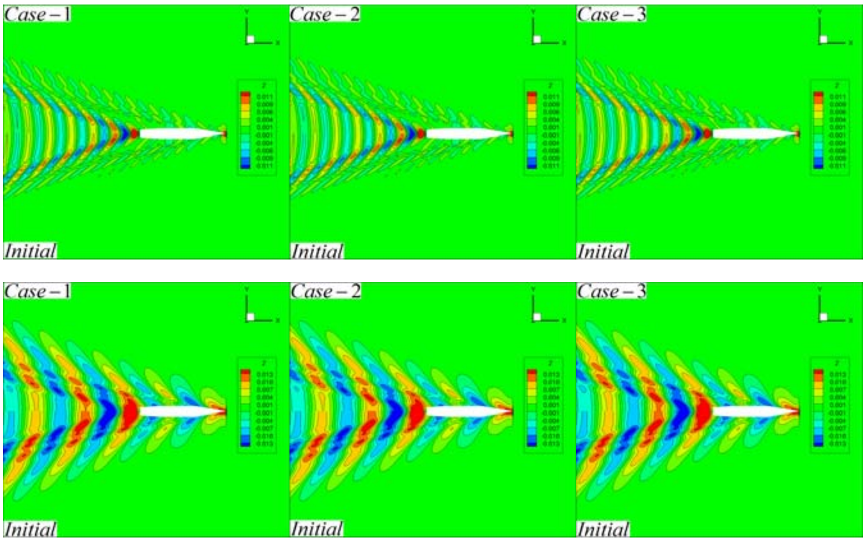


Fig. 8 Comparison of the free surface predicted by NM theory between original hull and case-1 at two speeds

CONCLUSIONS

A numerical multi-objective optimization tool, OPTShip-SJTU[14,15] has been developed and utilized here to optimize the resistance performance at two speeds for ONR Tumblehome model 5613. During the procedure of optimization, FFD method is used to modify bulbous bow and aft body of ship hull, and it is sufficiently flexible to generate a series of realistic alternative hull forms with just four design variables involved. Neumann-Michell theory is employed to evaluation the wave-making resistance with the advantages of efficiency and accuracy. Optimal Latin hypercube design, kriging model and a muti-objective genetic algorithm NSGA-Ⅱhave been integrated into this tool and successfully used in present work. Three of optimal cases are chosen from the pareto solution set for validation. It shows the multi-objective optimization conducted by OPTShip-SJTU is reliable and useful, and the further work will focus on the application of URANS-based simulation tools in hull optimization.

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