HULL FORM OPTIMIZATION OF JBC BASED ON RESISTANCE AND PROPULSION PERFORMANCES

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Introduction

In the ship design process, hull form design is of vital importance. In recent years, with the huge development of computer technology and calculation theories, the Simulation-Based-Design (SBD) technology is becoming possible rather than empirical or semi-empirical formulas. It is a new design way which integrates hull form transformation method, optimization technology and numerical simulation module.

If we consider viscosity, Navier-Stokes equations are the fundamental equations to solve using numerical methods. OpenFOAM is the leading free, open source software for computational fluid dynamics (CFD) including a lot of standard solvers, for example, *pimpleDyMFoam* solver is a transient solver for incompressible, turbulent flow of Newtonian fluids on a moving mesh while *interDyMFoam* solver is a solver for 2 incompressible, isothermal immiscible fluids using a VOF (volume of fluid) phase-fraction based interface capturing approach [1].

In this study, we focus on the resistance and propulsion performances of the hull. Although we can simulate the new hulls sailing in calm water including free surface using *interDyMFoam* solver, we finally decide to use *pimpleDyMFoam* solver and double model instead of the whole ship model. The reasons are as follows: One is that the wave-making resistance represents too small a percentage of the total resistance when the Froude number is small, the other is that the propeller disk has a relatively big distance to the still water level, so the wake field cannot be much affected by the free surface. As a result, it can save most of computational time with relatively high fidelity.

Furthermore, in order to do the efficient optimization, one method is to construct a relatively simple surrogate model instead of the simulations of a large number of sample points to find the relationship, which is often with strong nonlinearity, between the design variables (input) and the objective functions (output). The model requires very little time to evaluate the objective function. The most widely used surrogate models are the polynomial-based models: the response surface model and the Kriging model.

In this paper, the Japan Bulk Carrier (JBC) is considered as the initial hull. The hull form can be globally or locally deformed while the wetted surface area and displacement are constrained within a certain range. A practical hydrodynamic optimization tool OPTShip-SJTU [2] are applied for the hull form optimization. Here, the free-form deformation (FFD) method and shifting method are used as parametric hull surface modification techniques in order to generate a series of hull forms subjected to geometric constraints. The parameters of the sample deformed hull forms are generated by the OLHS approach and their hydrodynamic performances are calculated by *pimpleDyMFoam* solver.

Hull form optimization is comprehensive technology. The OPTShip-SJTU solver is a self-developed tool based on C++ language for the ship hull form optimization, which has obtained national software copyright. The framework of OPTShip-SJTU is shown in Figure 1.

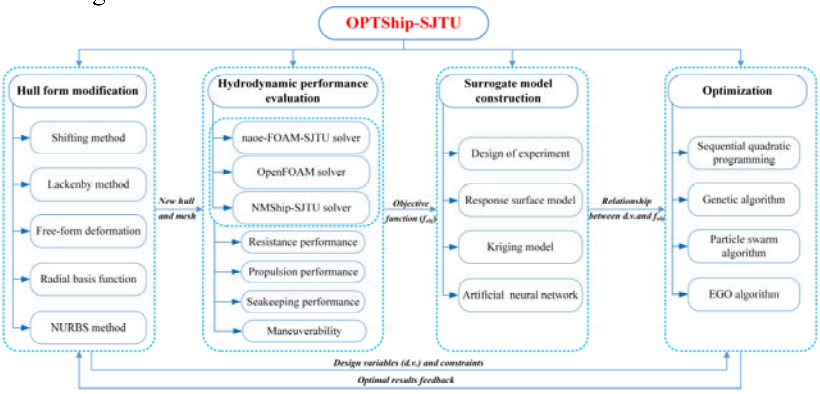


Figure 1: Framework diagram of OPTShip-SJTU

Optimization methods

Ship hull form transformation module is a bridge connecting ship performance evaluation module and optimization module. Once a series of design variables values are selected, ship transformation module needs to make rapid response to the certain set of design variables, that is, to modify the initial model to the new ones, and send them to the ship hydrodynamic performance evaluation module. The free form deformation method is proposed by Sederberg and Parry [3] that has been widely used in various fields including hull geometry reconstruction and other transportation tools. By changing the location of the control points, different new meshes of the hulls can be obtained easily. Furthermore, the shifting method can be applied to the global transformation of the hull form.

Hydrodynamic Performance Evaluation

Taking the initial hull as an example, the transformed hulls are evaluated similarly.

For pre-processing involving mesh generation, we use the utility *blockMesh*, supplied in OpenFOAM, to generate a rectangular background mesh for a cubic domain. In this study, it was set to $-L_{wl} \le x \le 4L_{wl}, 0 \le y \le L_{wl}, -L_{wl} \le z \le 0$, and the origin of the region is at the intersect of the still water level, central longitudinal section, and the bow part of the hull. Furthermore, and numbers of cells in each direction is (n_x, n_y, n_z) = (42,9,30). Then, we can use *snappyHexMesh* utility to do the ‘castellatedMesh’, ‘snap’, and ‘addLayers’ steps.

The boundary condition settings, calculation region and mesh are shown below.

Table 1: Boundary conditions of the case

Boundary	Velocity	Pressure
inlet	fixedValue	zeroGradient
outlet	zeroGradient	fixedValue
left	symmetryPlane	symmetryPlane
right	fixedValue	slip
top	symmetryPlane	symmetryPlane
bottom	fixedValue	slip
hull	fixedValue	zeroGradient

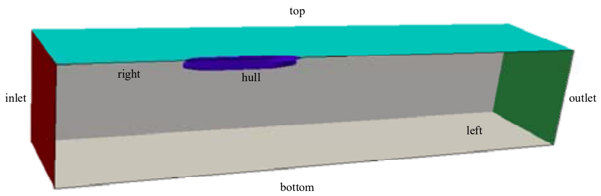


Figure 2: Calculation region of the case

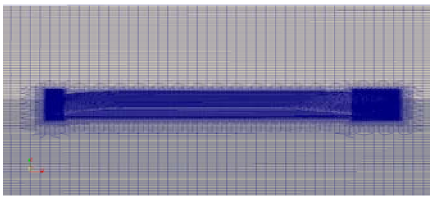


Figure 3: Mesh around the hull of the case

Surrogate Model Construction

As a kind of regression model, Kriging model is able to exploit the spatial correlation of data in order to predict the shape of the objective function based only on limited information. [4] Kriging exploits the spatial correlation of data in order to build interpolation; therefore, the correlation function is a critical element. The accuracy of the prediction value largely depends on the distance from sample points.

Optimization Method

At the stage of computing optimization, we first select 50 sample points in the design space by Optimal Latin Hypercube Sampling method (OLHS) design [5], and use the Kriging model instead of huge numerical calculation to make quick evaluations. Finally, the genetic algorithm NSGA-II [6] is selected as the optimization method, and after 300×200 individual evolutions, the ideal optimal hull forms can be obtained.

Objective Function

The optimization problem in this paper takes the JBC as the initial ship, which has the ship main dimensions of L_{wl}=7.125m, B=1.125m, D=0.625m, T=0.4125m in model scale, and the model can be seen in Figure 4.

Figure 4: Ship hull form of JBC

In this study, the objective functions are shown below,

$$\min \ F_t \tag{1}$$

$$\min \ w = \sqrt{\frac{\sum_{i=1}^{N}\left(u_{x,i} - \bar{u}_x\right)^2}{N\bar{u}_x^{\,2}}} \tag{2}$$

where F_t is the total resistance of the hull without considering free surface, and w is the normalized standard deviation of the velocity distribution in direction x at the propeller disk.

Design Variables

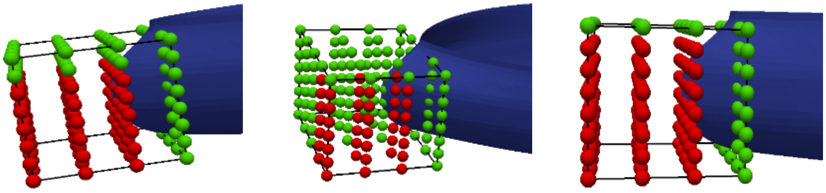
Optimization variables are used to control the free variation of the ship form in the design space. Ship transformation method in this paper is FFD and shifting method, involving one lattice (shown in Figure 5) at the bulbous bow. Red points are movable while green points are fixed.

Five optimization design variables, including alpha1, alpha2, X1, Y1, Z1, are summed up. The first 2 variables are for the shifting method, and the latter three control the change of the bulbous bow surface in three directions: *x*, *y* and *z*. In order to ensure that the hull form is within a reasonable range, the range of the design variables is specified in Table 2.

For instance, if X1=+0.005, then all the red points in Figure 5(a) move along the x-axis with a distance of +0.005m at the same time.

Table 2: The range of the 5 variables

Method	Variables	Min	Max
Shifting method	alpha1	0	0.06
	alpha2	0	0.06
FFD method	X1	-0.01	0.01
	Y1	-0.01	0.001
	Z1	-0.005	0.005



(a)bow-x direction (b) bow-y direction (c) bow-z direction

Figure 5: Schematic diagram of FFD method (Lattice and layout of control points)

Optimization result and analysis

We can finally use NSGA-II to get the Pareto front shown in Figure 6 and the corresponding values of the design variables are shown in Table 3.

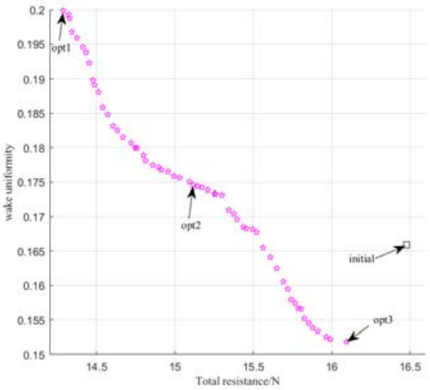
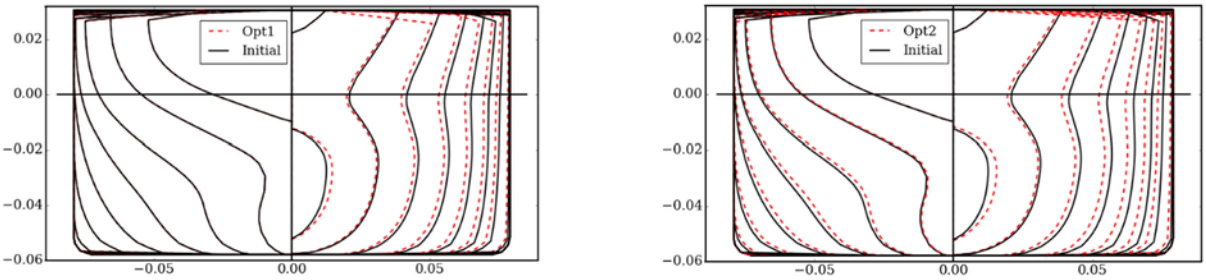


Figure 6: Pareto front of the optimization problem

Table 3: The comparisons of the design variables and the objective functions of initial and optimal hulls

Ship	alpha1	alpha2	X1	Y1	Z1	F_t/N	w	△F_t/%	△w/%
initial	0	0	0	0	0	16.4819	0.1660	0	0
opt1	0.0348	0.0600	-0.0023	-0.0003	-0.0007	14.2856	0.1999	-13.33%	20.39%
opt2	0.0547	0.0246	-0.0067	-0.0045	-0.0017	15.1159	0.1746	-8.29%	5.16%
opt3	0.0066	0.0008	-0.0100	0.0079	0.0032	16.0953	0.1519	-2.35%	-8.52%

The hull lines comparisons are shown in Figure 7. We can see from Figure 7 that the bulbous of the optimal hulls are fatter in the *y* direction than the initial one, and the fore part after the bulbous and also stern parts of the optimal hulls are a bit thinner than the initial one.



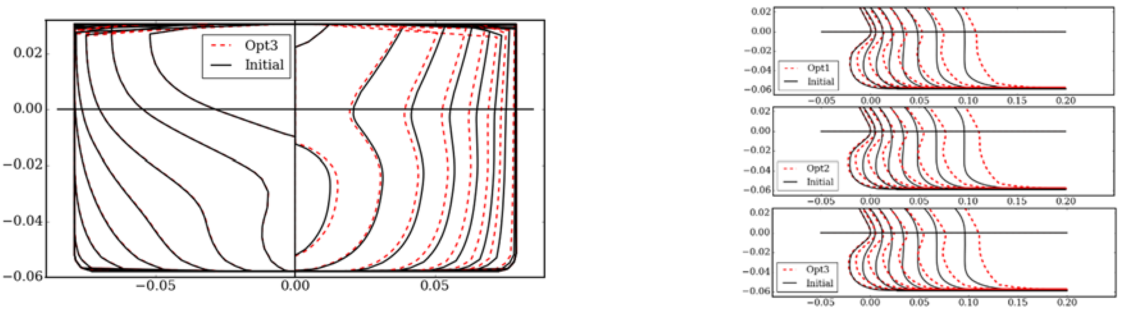
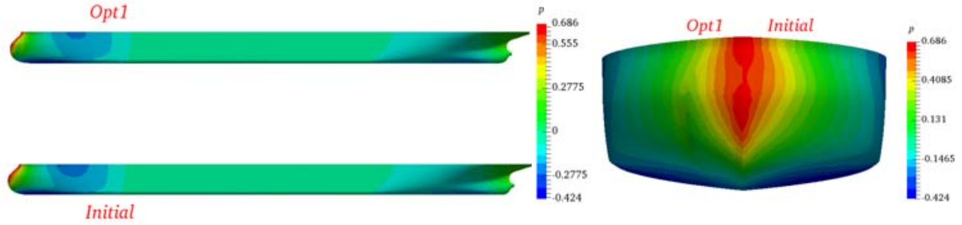


Figure 7: Hull line comparisons

We might as well compare the initial and some certain hull forms through their pressure and wake field information.



(a) (b)

Figure 8: Pressure distribution comparisons

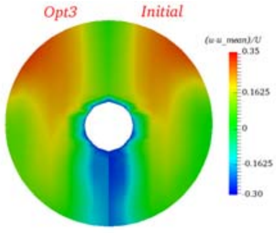


Figure 9: Wake field comparisons

Seen from Figure 8, the fore part of the optimal hull Opt1 has smaller high pressure and low pressure regions, which results in the lower resistance.

We can also know from Figure 9 that the velocity distribution in direction *x* at the propeller disk of the optimal hull Opt3 is more uniform than that of the initial one, which is good for the propulsion performance.

Conclusions

In this paper, the JBC is considered as the parent ship. The hull form can be globally and locally deformed while the wetted surface area and displacement are constrained within a certain range. Kriging approximate model is constructed which can reduce the computational cost. Finally, the multi-objective genetic algorithm is taken as the optimization technique leading to the optimal hull forms which have better resistance and propulsion performances.

The whole optimization process is implemented based on OpenFOAM and in-house optimization solver OPTShip-SJTU. It turns out that it’s convenient to use OpenFOAM to consider the hydrodynamic performances of the ship in the design period and OPTShip-SJTU has practical applications in the aspect of the optimization of ship hydrodynamic performances.

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