Proceedings of the Twenty-sixth (2016) International Ocean and Polar Engineering Conference **www.isope.org**
Rhodes, Greece, June 26-July 1, 2016

ISBN 978-1-880653-88-3; ISSN 1098-6189

Multi-Objective Hydrodynamic Optimization of Ship Hull Based on Approximation Model

*Jianwei Wu, Xiaoyi Liu and Decheng Wan**
State Key Laboratory of Ocean Engineering, School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University,
Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration, Shanghai, China
*Corresponding author

ABSTRACT

A practical multi-objective optimization tool, named OPTShip-SJTU, is utilized here to optimize both of the resistance and seakeeping performance for a surface combatant DTMB Model 5415. During the optimization procedure, free-form deformation (FFD) method is used as parametric hull surface modification technique to produce a series of alternative hull forms subjected to geometric constrains. The Neumann-Michell (NM) theory and an extension of Bales seakeeping ranking method are implemented in the evaluation module of the tool, and to predict the wave-making drag and Bales seakeeping rank factor R respectively. An optimized Latin hypercube sampling (OLHS) method is employed to generate 60 samples within the design space, and an approximation model is established in terms of these samples and corresponding predictions. A muti-objective genetic algorithm, NSGA-Ⅱ, is adopted to produce pareto-optimal front. The numerical optimization results are analyzed, and the availability of the OPTShip-SJTU is confirmed by this application.

KEY WORDS: OPTShip-SJTU; resistance; seakeeping; approximation model;

INTRODUCTION

The optimization of hull forms to improve the hydrodynamic performances has attracted attention in the recent years. In the past, a large number of alternative hulls were proposed according to the experience of ship designers and tested by model experiments before the final design was obtained, obviously, this method is in low effect and uneconomical. At present, with the rapid development of numerical methods and optimization algorithms, advanced modification methods, evaluation tools and optimizers have been proposed and integrated together to form various numerical optimization platforms, and they have been presented in a huge body of literature.

Kim *et al.* (2010) used two approaches including shifting method and radial basis function interpolation to modify the hull surface, and a practical CFD tool and Bales seakeeping ranking method were used to predict the objective functions associated with resistance and seakeeping. Eventually, valid results were obtained using the MOGA algorithm for optimization. Tahara *et al.* (2011) took a fast catamaran as the initial design and the numerical optimization was performed based on an URANS solver, a potential flow solver and global optimization (GO) algorithms. The HSSL-B geometry was successfully optimized and an experimental campaign was carried out for validation. Zhang *et al.* (2015) studied the minimum total resistance hull form design method based on potential flow theory of wave-making resistance and considering the effects of tail viscous separation, and the nonlinear programming method was chosen as the optimization scheme. Campana *et al.* (2006) present the fundamental elements of a SBD environment for shape optimization. Both of the CFDSHIP-Iowa and MGShip were used as simulation tools, and CAD-free and CAD-based techniques had been adopted for shape grid manipulation. Additionally, GA approach was utilized in the computations and approximation model management optimization (AMMO) was employed to reduce the computational efforts. Based on above techniques, our in-house hydro-dynamic optimization tool, OPTShip-SJTU, was developed for numerical multi-objective optimization of ship hull (Wu, Liu and Wan, 2015).

In this paper, the practical multi-objective optimization tool, OPTShip-SJTU, is utilized to optimize both of the resistance and seakeeping performance for a surface combatant DTMB Model 5415 which is adopted as the initial hull form and the geometry of hull form is modified by FFD method globally and locally. This method is flexible enough to generate a series of realistic hull forms and just a few number of design variables are involved. One of the accurate approximation models, kriging model, is constructed based on the samples given by OLHS method and predicted by evaluation module including the NM theory and Bales seakeeping ranking method, and during the optimization process the kriging model will be used to provide the estimates. With respect to optimizer, a muti-objective genetic algorithm, NSGA-Ⅱ, is adopted to produce pareto-optimal front. Eventually, the optimal hull forms with obvious drag reductions and seakeeping improvements are obtained and verified by the two evaluation methods.

MODIFICATION OF HULL GEOMETRY

A practical surface modification method plays an important role in the optimization process. The hull surface should be deformed with the method efficiently while just a few number of design variables involved for avoiding huge increase of complexity of the problem. In this paper, FFD approach (Sederbergm and Parry, 1986) is chosen to perform the deformation of solid geometric models in a free-form manner based on trivariate Bernstein polynomials, and is outlined below.

The FFD is defined in terms of a tensor product trivariate Bernstein polynomial. Fig. 1 shows a local coordinate system. The local coordinates of any point **X** is (*s*, *t*, *u*):

$$\mathbf{X} = \mathbf{X}_0 + s\boldsymbol{S} + t\boldsymbol{T} + u\boldsymbol{U} \tag{1}$$

These local coordinates can be computed as following:

$$s = \frac{\boldsymbol{T}\times\boldsymbol{U}(\mathbf{X}-\mathbf{X_0})}{\boldsymbol{T}\times\boldsymbol{U}\cdot\boldsymbol{S}},\ t = \frac{\boldsymbol{S}\times\boldsymbol{U}(\mathbf{X}-\mathbf{X_0})}{\boldsymbol{S}\times\boldsymbol{U}\cdot\boldsymbol{T}},\ u = \frac{\boldsymbol{S}\times\boldsymbol{T}(\mathbf{X}-\mathbf{X_0})}{\boldsymbol{S}\times\boldsymbol{T}\cdot\boldsymbol{U}} \tag{2}$$

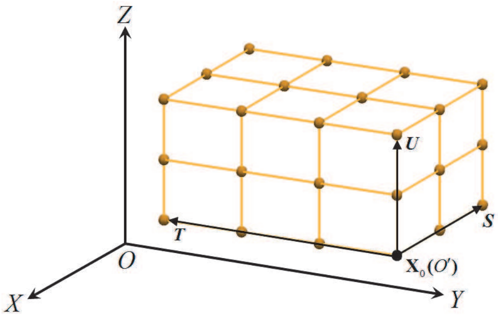


Fig. 1 Local coordinate system in FFD method

The objects needed to be deformed are completely wrapped by the parallelepiped, so, it is obvious that $0 < s, t, u < 1$. Next, the parallelepiped is cut into *l*, *m*, *n* parts along ***S***, ***T***, ***U*** directions respectively, and a series of control nodes $\mathbf{Q}_{i,j,k}$ are generated and imposed on a lattice. In Fig. 1, *l*=2, *m*=3, *n*=2, and the yellow spheres represent the control points whose Cartesian coordinates can be expressed as:

$$\mathbf{Q}_{i,j,k} = \mathbf{X}_0 + \frac{i}{l}\boldsymbol{S} + \frac{j}{m}\boldsymbol{T} + \frac{k}{n}\boldsymbol{U} \tag{3}$$

Thus, the Cartesian coordinates of any point **X** with local coordinates (*s*, *t*, *u*) can be computed using the control nodes:

$$\mathbf{X}(s,t,u) = \sum_{i=0}^{l}\sum_{j=0}^{m}\sum_{k=0}^{n} B_{i,j}(s)B_{j,m}(t)B_{k,n}(u)\mathbf{Q}_{i,j,k} \tag{4}$$

in which *B* represents Bernstein polynomial:

$$B_{i,n}(u) = \frac{n!}{i!(n-i)!}u^i(1-u)^{n-i} \tag{5}$$

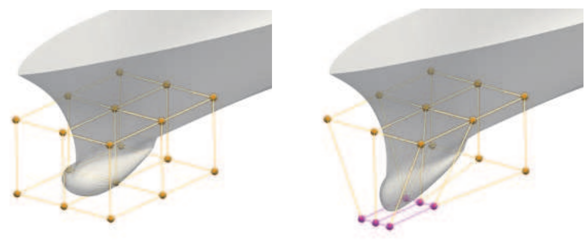
The deformation is performed by moving the control nodes $\mathbf{Q}_{i,j,k}$ from their original latticial positions, and the deformed position $\mathbf{X}_{ffd}$ of any point **X** (*s*, *t*, *u*) can be obtained as following:

$$\mathbf{X}_{ffd} = \sum_{i=0}^{l}\sum_{j=0}^{m}\sum_{k=0}^{n} B_{i,j}(s)B_{j,m}(t)B_{k,n}(u)\mathbf{Q}'_{i,j,k} \tag{6}$$

where $\mathbf{Q}'_{i,j,k}$ denotes the new locations of control nodes in Cartesian coordinates.

This technique can be used for modification both locally and globally, whether the global hull surface or part of it can be embedded into a parallelepiped on which the control points are imposed, and the surface will be modified along with the movements of the control points. Consequently, the displacements of control points are utilized as design variables within this approach.

An application of FFD approach to modify a ship bow was illustrated in Fig. 2. The surface to be deformed is wrapped by a parallelepiped, and changed with the movements of control points. The purple spheres represent the movable control points while the yellow spheres represent the fixed control points.



(a) Initial (b) Modified

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

NEUMANN-MICHELL THEORY

A ship advancing at a constant speed along a straight line in calm water of infinite depth and lateral extent is considered here, and the wave-making drags can be forecasted efficiently by the Neumann-Michell (NM) theory (Nobless *et al.*, 2013). 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 routine application to early-stage ship design and optimization. Kim *et al.* (2011) have integrated NM theory to optimization tool to evaluate the objective functions and obtained optimal solutions with obvious improvements on hydrodynamic performances.

The Neumann-Michell potential representation

Here we offer the flow potential representation according to NM theory:

$$\tilde{\phi} = \tilde{\phi}^W + \tilde{\phi}^L = \tilde{\phi}_H + \tilde{\psi}^W + \tilde{\psi}^L \tag{7}$$

where, the three components are defined as :

$$\tilde{\phi}_H \equiv \int_{\Sigma^H} G\, n^x\, da - \int_{\Sigma^F} G\, \pi^\phi\, dxdy$$

$$\tilde{\psi}^L \equiv -\int_{\Sigma^H} \phi\mathbf{n}\cdot\nabla L da + F^2\int_\Gamma \frac{\phi L_x n^x dl}{\sqrt{(n^x)^2+(n^y)^2}} \tag{8}$$

$$\tilde{\psi}^W = \int_{\Sigma^H} (\phi_t \mathbf{d}_* + \phi_d \mathbf{t}_*)\cdot \mathbf{W}da$$

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

$$\tilde{\phi} \approx \tilde{\phi}_H + \tilde{\psi}^W \equiv \tilde{\phi}_H^L + \tilde{\phi}_H^W + \tilde{\psi}^W \equiv \tilde{\phi}_H^L + \tilde{\phi}^W \tag{9}$$

Validation of the Neumann-Michell

The application and validation study for NM theory have been reported in many literature (Nobless *et al.*, 2013; Huang *et al.*, 2013; Yang *et al.*, 2013). In order to verify the reliability of the program based on NM theory, a validation is carried out before the optimization. DTMB

Model 5415 is chosen as the benchmark hull, and the sum $C_f + C_w$ 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 comparison shows that this practical evaluation approach based on NM theory is quite qualified for the optimization work. It can provide sufficiently accurate drag coefficients with high efficiency, which is very important to optimization at early stage.

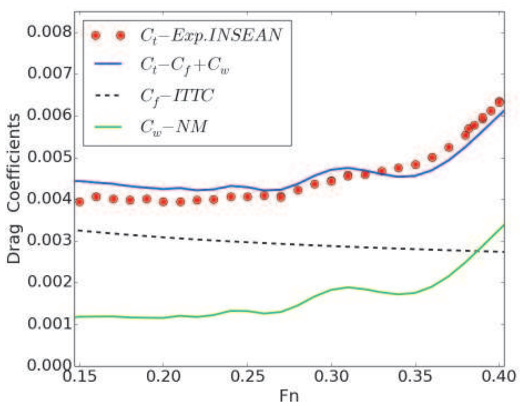


Fig. 3 Comparison of drag coefficients for the DTMB Model 5415

EXTENSION OF THE BALES SEAKEPPING RANKING METHOD

The original work of Bales (1980) is such an approach that is available for evaluating the seakeeping of ship in terms of six underwater hull characteristics. An extension of the Bales seakeeping rank factor concept was proposed by Walden (1983). This work discussed a means of calculating R factors based on a more complete hull form description, and the effect of displacement was considered. At present study, the variation of displacements of new hulls generated during the optimization process is less than 1%, but there are still tiny differences of displacements among optimal and initial hulls, thus we hope to compare the seakeeping characteristics of different size destroyer type ships by using this method.

The R factor predictor equation can be expressed as:

$$R = 8.422 + 45.104C_{WF} + 10.078C_{WA} - 378.465\frac{T}{L} + 1.273\frac{c}{L} - 23.501C_{VPF} - 15.875C_{VPA} + 12.9\frac{(\Delta - 4300)}{4300} \quad (10)$$

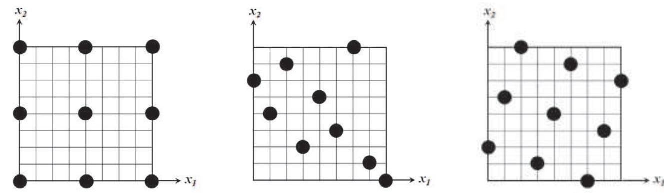
where C_{WF} is waterplane coefficient forward of amidships; C_{WA} is waterplane coefficient aft of amidships; *T/L* is draft to length ratio; *c/L* is cut-up ratio; C_{VPF} is vertical prismatic coefficient forward of amidships; C_{VPA} is vertical prismatic coefficient aft amidships; Δ is the displacement of ship. The better hull owns a larger value of R.

OPTIMIZATION MODULE

The optimization module plays a relevant role in the optimization tool. The aim of this module is to minimize or maximize objective functions during the optimization process.

Experimental design method

The design of experiment (DOE) is the best way to produce simulation samples for high accurate surrogate model used during the optimization. Many DOE methods have been proposed. In this paper, a modified Latin hypercube design, named optimal Latin hypercube sampling (OLHS) method proposed by Jin *et al.* (2005) is employed for sampling. The optimal Latin hypercube design is illustrated in Fig. 4 for a configuration with two factors and nine design points. Fig.3 (a) shows the standard orthogonal array and Fig. 4(b) shows the random Latin hypercube design. The optimal Latin hypercube is shown in Fig. 4(c), and the design points cover all levels of each factor as well as spread evenly within the design space.



(a) 3-level orthogonal array (b) Random Latin hypercube (c) Optimal Latin hypercube

Fig. 4 Three types of experimental design method

Mathematics of kriging model

Kriging model (Simpson *et al.*, 2001) is developed from mining and geostatistical applications involving spatially and temporally correlated data. This model combines a global model and a local component:

$$y(x) = f(x) + z(x) \quad (11)$$

where $y(x)$ is the unknown function of interest, $f(x)$ is a known approximation function of x, and $z(x)$ is the realization of a stochastic process with mean zero, variance σ^2, and non-zero covariance. With $f(x)$ and $z(x)$, the kriging model can build the surrogate model between the input variables and output variables.

The kriging predictor is given by:

$$\hat{y} = \hat{\beta} + \mathbf{r}^{\mathrm{T}}(x)\mathbf{R}^{-1}\left(\mathbf{y} - \mathbf{f}\hat{\beta}\right) \quad (12)$$

where y is an n_s-dimensional vector that contains the sample values of the response; $\mathbf{f}$ is a column vector of length n_s that is filled with ones when $\mathbf{f}$ is taken as a constant; $\mathbf{r}^{\mathrm{T}}(x)$ is the correlation vector of length n_s between an untried x and the sampled data points $\{x^{(1)}, x^{(2)}, \ldots, x^{(n_s)}\}$ and is expressed as:

$$\mathbf{r}^{\mathrm{T}}(x) = \left[R\left(x, x^{(1)}\right), R\left(x, x^{(2)}\right), \ldots, R\left(x, x^{(n_s)}\right),\right]^{\mathrm{T}} \quad (13)$$

Additionally, the Gaussian correlation function is employed in this work:

$$R(x^i, x^j) = \mathbf{exp}\left[-\sum_{k=1}^{n_{dv}} \theta_k \left|x_k^i - x_k^j\right|^2\right] \quad (14)$$

In equation (12), $\hat{\beta}$ is estimated using equation (15):

$$\hat{\beta} = \left(\boldsymbol{f}^{\mathrm{T}}\mathbf{R}^{-1}\boldsymbol{f}\right)^{-1}\boldsymbol{f}^{\mathrm{T}}\mathbf{R}^{-1}\boldsymbol{y} \quad (15)$$

The estimate of the variance $\hat{\sigma}^2$, between the underlying global model $\hat{\beta}$ and y is estimated using equation (16):

$$\hat{\sigma}^2 = \left[\left(y - f\hat{\beta} \right)^T R^{-1} \left(y - f\hat{\beta} \right) \right] \Big/ n_s \tag{16}$$

where $f(x)$ is assumed to be the constant $\hat{\beta}$. The maximum likelihood estimates for the θ_k in equation (14) used to fit a kriging model are obtained by solving equation (17):

$$\max_{\theta_k > 0} \Phi(\theta_k) = -\left[n_s \ln\left(\hat{\sigma}^2\right) + \ln|\mathrm{R}| \right] \Big/ 2 \tag{17}$$

where both $\hat{\sigma}^2$ and $|\mathrm{R}|$ are functions of θ_k. While any value for the θ_k create an interpolative kriging model, the "best" kriging model is found by solving the k-dimensional unconstrained, nonlinear, optimization problem given by equation (17).

Optimization algorithm

In present work, a non-dominated sorting genetic algorithm, named NSGA-II algorithm is adopted to guide the optimization procedure. It has been proposed by Deb *et al*. (2000) and widely applied in lots of optimization problems.

OPTIMIZATION PRINCIPLES

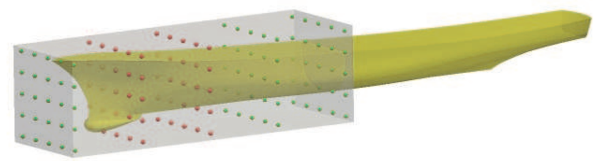
The initial design is DTMB Model 5415, which is conceived as a preliminary design for a navy surface combatant, and a large amount of experimental results have been obtained in an international cooperative project. It is notable that the length of ship model is 5.72m, and it's just as same as the one adopted in previous experiment performed by INSEAN. The initial hull is illustrated in Fig. 5.

Fig. 5 Geometry of DTMB Model 5415

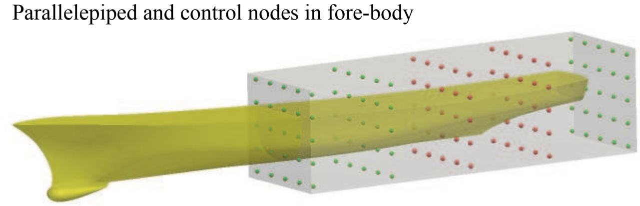
In this study, the geometry of ship hull surface is represented with unstructured meshes. FFD method is utilized to modify the nodes on the hull surface globally and locally, so, three parallelepipeds are established and reported in Fig. 6. For modifying the global ship, two parallelepipeds (Fig. 6 (a), Fig. 6 (b)) containing 125 control points are used here where the green control nodes are fixed and the red nodes have longitudinal freedom. 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 (6), then new hull surface will be obtained. It is notable that these red control nodes are move towards unity, and the amount of the movement x_1,x_2 (two parallelepipeds respectively) is regards as two of the design variables. Besides, the third parallelepiped (Fig. 6(c)) is located near the bow, and 200 control nodes are imposed in it while the fixed ones colored with green and the moving ones colored with red. Similarly, three other design variables x_3, y_1,z_1 can be derived from Fig. 6(c), and they determinate the displacements of movable control nodes (red) in the x, y, z directions respectively. The shape of ship bow will be modified with the movement of control nodes. A summary of these five design variables is reported in Table. 1. The first two ones modify the hull surface globally while the final three ones deform the ship bow locally, and they are applied to the hull at the same time.

Table 1. Summary of the design variables

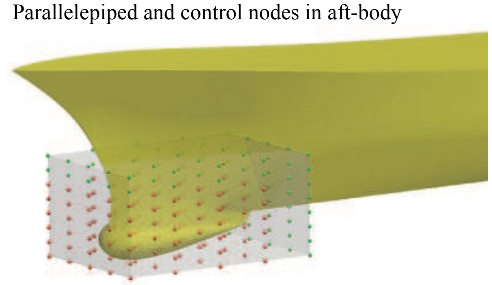
Design Variables	Range	Note
x_1	[-0.012, 0.012]	Displacement in x direction in Fig. 5 (a)
x_2	[-0.012, 0.012]	Displacement in x direction in Fig. 5 (b)
x_3	[-0.010, 0.010]	Displacement in x direction in Fig. 5 (c)
y_1	[-0.007, 0.007]	Displacement in y direction in Fig. 5 (c)
z_1	[-0.010, 0.010]	Displacement in z direction in Fig. 5 (c)



(a) Parallelepiped and control nodes in fore-body



(b) Parallelepiped and control nodes in aft-body



(c) Parallelepiped and control nodes near the bow

Fig. 6 Parallelepiped and control nodes using in FFD method

The present work concentrates on multi-objective hydrodynamic optimization of a ship hull. The three objective functions have been chosen as the wave resistance at two speeds (Fr = 0.28, 0.41), and the modified Bales seakeeping ranking factor R.

$$\textbf{Min } f\left([\mathrm{x}]\right) = \left\{ f_{obj}^1, f_{obj}^2, f_{obj}^3 \right\} \tag{18}$$

$$f_{obj}^1 = C_{w1}, \quad at\ \ Fr = 0.28 \tag{19}$$

$$f_{obj}^2 = C_{w2}, \quad at\ \ Fr = 0.41 \tag{20}$$

$$f_{obj}^3 = -R \tag{21}$$

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 1%.

$$\text{s.t.}\quad g_1 = L_{pp}^{opt} - L_{pp}^{ini} = 0 \tag{22}$$

$$g_2 = T^{opt} - T^{ini} = 0 \tag{23}$$

$$g_3 = B^{opt} - B^{ini} = 0 \tag{24}$$

$$g_4 = \left| \frac{\nabla^{opt} - \nabla^{ini}}{\nabla^{ini}} \right| \le 1\% \tag{25}$$

$$g_5 = \left| \frac{S_{wet}^{opt} - S_{wet}^{ini}}{S_{wet}^{ini}} \right| \le 1\% \tag{26}$$

As mentioned above, the kriging models are established based on the 60 samples given by OLHS method. Model1 and Model2 are to evaluate the wave-making drag coefficients and Model3 is to predict the seakeeping factor R. In order to check the approximation capability of these kriging models, an error analysis is carried out using the sample points, and the results including the maximum absolute error, the average absolute error and the root mean square error (MSE) are listed in Table. 2.

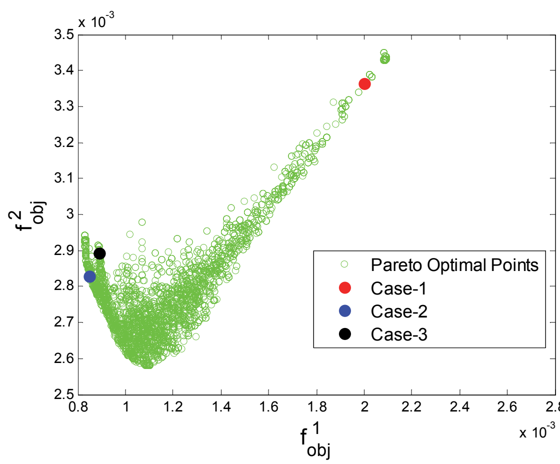
Table 2. Results of error analysis for kriging model

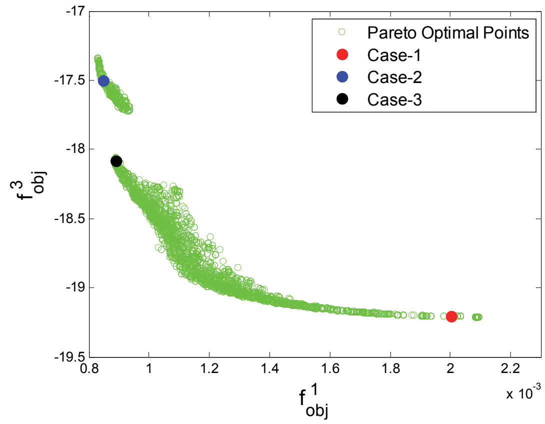
	Model1	Model2	Model3
Max ABS(error) ($\times10^{-16}$)	0.869	0.782	0.622
Avg ABS(error) ($\times10^{-17}$)	0.857	0.768	0.702
root MSE ($\times10^{-16}$)	0.148	0.134	0.116

Then the NSGA-II algorithm is adopted to guide the optimization procedure. The crossover rate is 0.8 and the mutation rate is 0.10. The number of generations is set as 300 while the size of population is 400, thus, 400×300 individuals will be generated and evaluated before the final results of optimization are obtained.

RESULTS

The pareto front is obtained base on the populations generated during the optimization processing. The relationship of any pair of objective functions is shown in Fig. 7, and a strong nonlinearity can be detected from it.





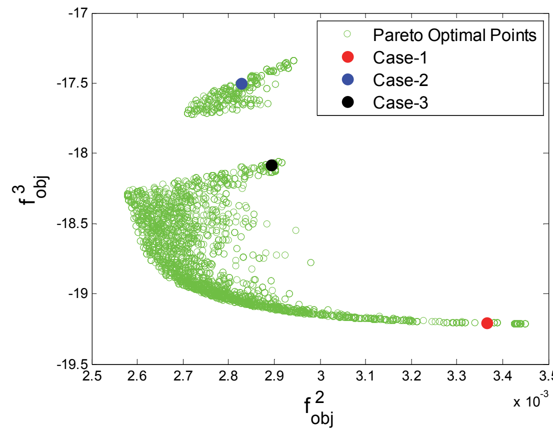


Fig. 7 Pareto front and selected cases in objective function space

Three optimal cases denoted as Case-1, Case-2 and Case-3 are chosen for further analysis. They scatter in Fig. 7 and relatively large differences exist in the values of objective functions among these cases. The comparisons of body plans and profile plans between the initial design and the optimal hull forms are illustrated in Fig. 8 and Fig. 9. It can be observed from the figure that the widths of domes significantly decrease in Case-2 and Case-3, while the width of dome for Case-1 almost keeps constant. The front body tends to be fatter for Case-1 and more slender for Case-2. It is notable that the geometric constraints have been satisfied in these pareto solutions including the three cases, and the value of design variables and variations on the geometric features related to Case-1, Case-2 and Case-3 are reported in Table. 3.

Table 3. Design variables and variations on the geometric features

	Case-1	Case-2	Case-3
Variable1	-0.01315	0.00788	-0.00112
Variable2	-0.00503	-0.00223	0.00326
Variable3	-0.00075	-0.00594	-0.00491
Variable4	0.00038	0.00011	0.00095
Variable5	-0.00272	-0.01458	-0.01467
Displacement %Original	+0.30%	-0.71%	-0.84%
Wetted area %Original	+0.91%	-0.38%	-0.04%

The optimization results are obtained based on kriging model, and the NM theory and modified Bales ranking method are employed to investigate drag and seakeeping performance of the three solutions. The predictions are presented in Table 4.

It can be known from the Tabel 4 that the resistance performances at Fr=0.4 in all three cases are improved, while the wave drag at low speed for Case-1 has a huge increase and the seakeeping for Case-2 decreases slightly. In fact, only Case-3 provides the consistent improvements for all the three objective functions. The multi-objective optimization algorithm just products pareto optimal solutions which confirm the concept of pareto optimality, consequently, such optimal hulls with detects for some objective functions can be offered (e.g. Case-1 and Case-2), and it is essential to screen these pareto optimal solutions to ensure the final choice is a perfect one.

Table 4. Predictions of drag and seakeeping performance

	Fr=0.28			Fr=0.41			R
	C_w ($\times 10^{-3}$)	C_f ($\times 10^{-3}$)	C_t ($\times 10^{-3}$)	C_w ($\times 10^{-3}$)	C_f ($\times 10^{-3}$)	C_t ($\times 10^{-3}$)	
Origin	1.36	2.91	4.28	3.47	2.73	6.20	17.53
Case-1	2.00	2.91	4.91	3.36	2.73	6.09	19.21
improvement %	*-46.7%*		*-14.9%*	*3.2%*		*1.8%*	*9.6%*
Case-2	0.85	2.91	3.76	2.83	2.73	5.56	17.50
improvement %	*37.9%*		*12.1%*	*18.6%*		*10.4%*	*-0.2%*
Case-3	0.89	2.91	3.80	2.89	2.73	5.62	18.08
improvement %	*34.8%*		*11.1%*	*16.7%*		*9.4%*	*3.1%*

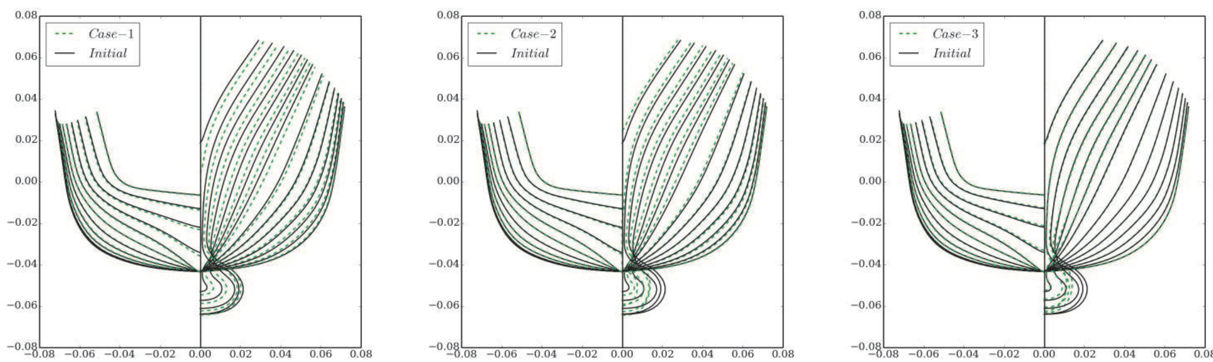


Fig. 8 comparisons of body plans between the initial design and the optimal hull forms

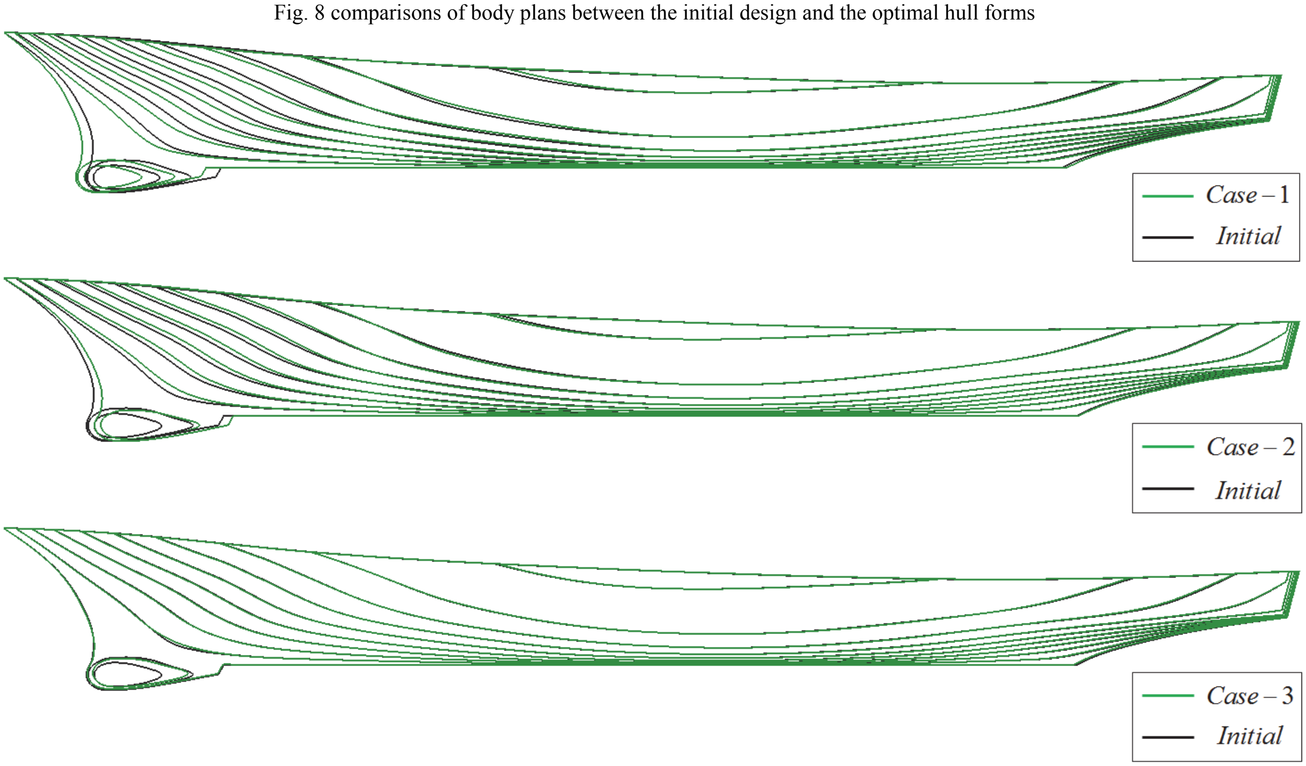


Fig. 9 comparisons of profile plans between the initial design and the optimal hull forms

COCLUSIONS

In this paper, our in-house numerical multi-objective optimization tool, OPTShip-SJTU is utilized here to optimize both of the resistance and seakeeping performance for a surface combatant DTMB Model 5415.

The FFD method has performed well in the modification of the global surface and the shape of the sonar dome. The Neumann-Michell theory is employed to evaluation the wave-making resistance with the advantages of efficiency and accuracy, and an extension of Bales seakeeping ranking method, considering the effect of displacement, has been implemented in this tool to predict the Bales seakeeping rank factor R. An experimental deign with optimal Latin hypercube method, kriging model and a muti-objective genetic algorithm NSGA-Ⅱ have been integrated into this tool and successfully used in present work. Three of the pareto solutions are chosen for validation, and the validity and high effectiveness of the optimization based on kriging model are proved by this application.

Further work will focus on the accuracy of the approximation model. High-fidelity simulation tools based on the URANS equations will be needed to evaluation the performances of samples, thus, better optimal designs with higher practicality and reliability can be obtained.

ACKNOWLEDGEMENTS

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), Innovative Special Project of Numerical Tank of Ministry of Industry and Information Technology of China (2016-23) and Foundation of State Ley Laboratory of Ocean Engineering (GKZD010065), to which the authors are most grateful.

REFERENCES

Bales, NK (1980). "Optimizing the seakeeping performance of destroyer-type hulls," *Proceedings of the 13th Symposium on Naval Hydrodynamics*.

Campana, EF, Peri, D, Tahara, Y, Stern, F (2006). "Shape optimization in ship hydrodynamics using computational fluid dynamics," *Computer Methods in Applied Mechanics & Engineering*, 196(1-3), 634-651.

Deb, K, Agrawal, S, Pratap, A, Meyarivan, T (2000). "A fast elitist non-dominated sorting genetic algorithm for multi-objective optimization: NSGA-II," *Lecture notes in computer science*, 1917, 849-858.

Jin, R, Chen, W, Sudjianto, A (2005). "An efficient algorithm for constructing optimal design of computer experiments," *Journal of Statistical Planning and Inference*, 134(1), 268-287.

Huang, FX, Yang, C, Noblesse, F (2013). "Numerical implementation and validation of the Neumann-Michell theory of ship waves," *European Journal of Mechanics*, 42(6), 47-68.

Kim, H, Yang, C, Noblesse, F (2010). "Hull form optimization for reduced resistance and improved seakeeping via practical designed-oriented CFD tools," *Crand Challenges in Modeling and Simulation*, 385-375.

Kim, H, Yang, C, Jeong, S, Noblesse, F (2011). "Hull form design exploration based on response surface method," *Proceedings of the 21st International Offshore Polar Engineering Conf,* ISOPE, 4.

Noblesse, F, Huang, FX, Yang, C (2013). "The Neumann-Michell theory of ship waves," *Journal of Engineering Mathematics*, 79(1), 51-71.

Sederbergm, TW, Parry, SR (1986). "Free-form deformation of solid geometric models," *Proceedings of the 13st Annual Conference on Computer Graphics and Interactive Techniques, SIGGRAPH*, 20(4), 151-160.

Simpson, TW, Mauery, TM, Korte, JJ, Mistree, F (2001). "Kriging models for global approximation in simulation-based multidisciplinary design optimization," *AIAA Journal*, 39(12), 2233-2241.

Tahara, Y, Peri, D, Campana, EF, Stern, F (2011). "Single- and multiobjective design optimization of a fast multihull ship: numerical and experimental results," *Journal of Marine Science & Technology*, 16(16), 412-433.

Walden, DA (1983). "Extension of the Bales seakeeping rank factor concept," *Proceedings of the 20th American Towing Tank Conference*.

Wu, JW, Liu, XY, Wan, DC (2015). "Manual of Ship Hull Optimization Tool: OPTShip-SJTU," Technical Report, Shanghai Jiao Tong University.

Yang, C, Huang, FX, Noblesse, F (2013). "Practical evaluation of the drag of a ship for design and optimization," *Journal of Hydrodynamics,* 25(5), 645-654.

Zhang, BJ, Zhang, ZX (2015). "Research on theoretical optimization and experimental verification of minimum resistance hull form based on Rankine source method," *International Journal of Naval Architecture & Ocean Engineering*, 7(5), 785-794.