A NURBS-based Hull Surface Modification Method for Hydrodynamic Optimization

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ABSTRACT

In modern computer aided ship design system, ship hull forms are mostly represented by the Non-Uniform Rational B-Spline surfaces and saved in IGES file format for data exchange between different CAD/CAM systems. Ship hull forms represented by NURBS surfaces have many good properties including visually fair and perfectly smooth compared with hull surfaces represented by discrete meshes. The local and global deformation of NURBS surfaces is simple by relocating the NURBS control points, changing the weight of control points, which possesses strong geometric explanation and is suited for the hydrodynamic optimization of ship hull forms. Therefore, a NURBS-based hull surface modification method is developed and integrated into an in-house solver OPTShip-SJTU for the hydrodynamic optimization of ship hull forms. The developed method is applied to the hydrodynamic optimization of Series 60 model. The optimization results demonstrate that the developed method is efficient and flexible for the deformation of hull surfaces and is suited for the optimization of real life ship.

KEY WORDS: NURBS; Radial basis function interpolation method; Ship hull form optimization; OPTShip-SJTU solver;

INTRODUCTION

With the development of computer technology and computational fluid dynamics, the CFD-based hydrodynamic optimization of ship hull forms has become a very powerful tool for the design of hull lines. It can be applied to the optimization of ship hull forms in terms of total resistance and sea-keeping performance in the preliminary stage. With the ship industry paying more and more attention to energy conservation and emission reduction such as energy efficiency design index proposed by IMO, the CFD-based hydrodynamic optimization of ship hull forms will play a more important role in the future. In general, the CFD-based hydrodynamic optimization of ship hull forms consists of four modules (Yang, 2016) including a hull surface representation and modification module, a hydrodynamic evaluation module, a surrogate module, and an optimization module. Among them, the hull surface modification module is used to modify the prototype hull forms to produce new hull forms in terms of hydrodynamic performance and design constraints. It is obvious that the ultimate optimization results are highly determined by the efficiency and quality of the hull surface modification module. The representation of hull model can be classified into two categories (Harries-Abt and Hochkirch, 2004): conventional modeling and parametric modeling. Parametric modeling defines hull model in a high level using form parameters. It can use few design variables to achieve the global deformation of ship hull forms and every form parameter has a specific meaning. But it is hard to achieve the local deformation of hull surfaces such as in the bow and stern. On the other hand, the typical example of conventional hull geometry modeling is ship hull forms represented by NURBS surfaces, which uses points to define curves and uses curves to define surfaces forming hierarchical structure. The NURBS surfaces have a simple and uniform mathematical expression to represent any complex surface as it is a mapping from two dimensional parameter space to surface in three-dimensional space defined by B-spline basis function, knot vectors of parameters, NURBS control points, and weights of control points (Piegl and Tiller, 2012). It uses piecewise rational polynomials to avoid using high degree formula to fit complex surfaces and meet geometry constraints, which allows for the local deformation of hull surfaces by moving the control points and changing the weights. There are two hull surface modification method based on NURBS. One is directly moving the NURBS control points of hull surfaces. Kim (2009) selected 31 NURBS control points of Wigley hull as design variables to optimize the total drag coefficient at three given speed. Park and Choi (2013) used the movement of NURBS control points along x and z directions in the ship bow as design variables to optimize Series 60 model in terms of resistance. Wang (2015) used the direct NURBS-based hull surface modification method to generate a bulbous bow and a stern in Wigley hull. Then the hull with initial bulbous bow was optimized using radial basis function interpolation method (RBF). The direct NURBS-based hull surface modification method can achieve large and local deformation of hull surfaces. But it needs to define many design variables, which increases the computation cost. The other one is moving the NURBS control points of hull surfaces combined with other deforming methods including the RBF method, the Free Form Deformation Method and the shifting method. Noble and Clapworthy (1999) used the Free Form Deformation method (FFD) to move the control points of NURBS surfaces, which avoids the limitations of
ordinary FFDs. Kim and Yang (2013) applied the shifting method and the RBF method to move the NURBS control points of Model 5279 hull to achieve the global and local deformation of ship hull forms. The optimal hull with a bulbous bow and a stern end bulb was obtained. Yang (2016) applied the NURBS-based modification technique to the optimization of a series of Joint High Speed Sealift with different bow configuration. Cheng et al (2018) employed the radial basis function interpolation method to the optimization of Series 60 model and reached a conclusion that the value of support radius of Wendland \( \psi_{3,1} \) basis function has a great impact on the deformation of hull surfaces. In order to avoid generating saddle-shaped surfaces during the modification of hull surfaces, the support radius should be twice the maximum length of the Delaunay triangulation edges. Pérez et al (2007) used the cubic B-spline curves to construct the body plan of bulbous bow subject to certain form parameters and the B-spline surfaces that fit these curves were constructed. Then the initial hull with bulbous bow generated above is optimized via CFD-based optimization method. Compared with the direct NURBS-based hull surface modification method, these methods have its merits. Only a small number of control points are required as design variables to achieve the flexible deformation of hull surfaces. The large deformation of hull surfaces can be achieved where various geometry constraints can be easily satisfied. The modified region can have a fairing connection with the original hull.

In this paper, a NURBS-based hull surface modification method combined with the RBF method is developed in C++ language and integrated to the in-house solver named OPTShip-SJTU, which is the software for the hydrodynamic optimization of ship hull forms. In order to validate the reliability and efficiency of this developed hull surface modification method, it is applied to the single-objective hydrodynamic optimization of the Series 60 model for reduced wave drag coefficient at \( Fr=0.27 \). Before the optimization process, the total drag coefficients of Series 60 model at a range of speeds are calculated by the fast CFD solver named NMShip-SJTU based on potential flow theory and are compared with model experiment data to validate the accuracy of the NMShip-SJTU solver in the prediction of the total drag coefficient. The RBF interpolation method is used to move the NURBS control points of the initial hull in the bow to generate a bulbous bow where the RBF fixed control points and the RBF movable control points are distributed properly around the bow of the hull to meet geometric constraints. Then the initial bulbous bow generated above is optimized in terms of wave drag coefficient. The hydrodynamic performance of the optimal bulbous bow is validated by the high-fidelity CFD solver named naoe-FOAM-SJTU (Shen et al, 2011) and the wave drag, total drag and wave pattern generated by the initial hull and the optimal hull with bulbous bow are compared and analyzed in detail.

SUMMARY OF SERIES 60 MODEL

The Series 60 model is served as a standard ship model by ITTC organization for model testing. Many ship model testing had been conducted by colleges and research institutions (Shen, 2015). There are many experiment data available about resistance at different speeds. The Series 60 model chosen in this paper is the same as the IHHR’s (Iowa Institute of Hydraulic Research) ship model. The principal dimensions are displayed in Table 1 and Fig. 1.

Table 1. Principal dimensions of Series 60 model (Model scale)

<table>
<thead>
<tr>
<th>Principal dimensions</th>
<th>Series 60 model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length between perpendiculars (( L_{pp} )) /m</td>
<td>3.0480</td>
</tr>
<tr>
<td>Length between water line (( L_{wl} )) /m</td>
<td>3.1010</td>
</tr>
<tr>
<td>Breadth between water line (( B )) /m</td>
<td>0.4060</td>
</tr>
<tr>
<td>Draught (( T )) /m</td>
<td>0.1630</td>
</tr>
<tr>
<td>Wetted surface area /m(^2)</td>
<td>1.6000</td>
</tr>
<tr>
<td>Volume of displacement /m(^3)</td>
<td>0.1214</td>
</tr>
<tr>
<td>Block coefficient</td>
<td>0.6000</td>
</tr>
</tbody>
</table>

The Series 60 model is represented by NURBS surfaces. In order to have a better understanding of the contents in the following section, the basic mathematical theory of NURBS surface is briefly introduced. A NURBS surface that is \( p \)-th degree in \( u \) direction and \( q \)-th degree in \( v \) direction is defined by (Piegl and Tiller, 2012):

\[
S(u,v) = \frac{\sum_{i=0}^{n} \sum_{j=0}^{m} N_{ij}(u) N_{ij}(v) P_{ij}}{\sum_{i=0}^{n} \sum_{j=0}^{m} N_{ij}(u) N_{ij}(v) \omega_{ij}} \tag{1}
\]

Where \( \{ P_{ij} \} \) form the control net of NURBS surface, \( \{ \omega_{ij} \} \) are the weight factors, \( \{ N_{ij} \} \) are the \( p \)-th-degree and \( q \)-th-degree B-Spline basis function, respectively, which is defined recursively as:

\[
N_{ij}(u) = \begin{cases} 1, & \text{if } u_i \leq u \leq u_{i+1} \\ 0, & \text{else} \end{cases} \tag{2}
\]

\[
N_{ij} = \frac{u - u_{ij}}{u_{i+1} - u_{ij}} N_{ij-1} + \frac{u_{i+1} - u}{u_{i+1} - u_{ij}} N_{ij+1} \tag{3}
\]

on the non-uniform knot vectors:

\[
U = \left\{ a_{p,i}, a_{p,i+1}, \ldots, a_{p,i+p-1} \right\} \tag{4}
\]

\[
V = \left\{ c_{q,i}, c_{q,i+1}, \ldots, c_{q,q+q-1} \right\} \tag{5}
\]

The rational B-Splines basis functions are piecewise on the knot vectors, so the movement of a control point only deforms surface near that point, which allows for the local deformation of hull surface. There are many algorithms to manipulate NURBS surface. For example, for a hull surface with sparse control points, it is useful to refine the control points in the bow by knot refinement method for the generation of bulbous bow. A various of NURBS surface manipulation techniques are integrated into the OPTShip-SJTU solver for the pre-processing of ship hull forms represented by NURBS surfaces.

HYDRODYNAMIC EVALUATION MODULE

The CFD-based hydrodynamic optimization of ship hull forms depends on the computation fluid dynamics to evaluate objective functions such

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Fig. 1 Series 60 model.
as drag and sea-keeping performance. In the optimization process, through the hull surface modification module, thousands of optional ship hull forms are generated and their hydrodynamic performances need to be calculated. It costs too much time and computation resources to evaluate objective functions through high-fidelity CFD solvers based on RANS/LES method. Thus a self-developed linear potential flow solver named NMShip-SJTU, which is based on the Neumann-Michell (NM) theory (Noblesse-Huang and Yang, 2013), is employed for the evaluation of hydrodynamic performance. The NM theory is the modification of the classical Neumann-Kelvin theory and is based on consistent linear flow model, which yields more realistic predictions of the ship drag, when comparing with experimental measurements. Before the optimization process, the validation of NMShip-SJTU (Zhang et al, 2014; Zhang et al, 2015) solver in the prediction of drag is carried out. The wave drag coefficient is calculated by NMShip-SJTU solver where the frictional resistance is evaluated by the ITTC 1957 Model-Ship Correlation Line (Yang-Huang and Noblesse, 2013):

The total resistance is approximated by the sum of wave drag and frictional resistance calculated above. The comparison of the total resistance of the Series 60 model at a range of Froude numbers between experiment data done by Wuhan University of Technology (WHUT) and values predicted by NMShip-SJTU solver is shown in Fig. 2.

The radial basis function is a type of scalar function that is symmetric along the radial direction, which is widely used in many fields including the fitting of large-scale scattered data, the numeric solution of partial differential equation, and the deformation of mesh in CFD. The value of the radial basis function depends on the Euclidean distance between any point X and the centre of points X_i. The general mathematical form of radial basis function can defined as:

\[
\phi(||X - X_i||), \quad i = 1, 2, ..., N
\]

where X_i is centre of the radial basis function and X is any point in Euclidean space. Applying this method to the NURBS-based hull surface modification, the interpolation function is expressed as follows:

\[
s(X) = \sum_{i=1}^{N} \lambda_i \phi(||X - X_i||) + p(X)
\]

where s(X) represents the displacement of NURBS control points. p(X) is a low-order polynomial that covers the translation and rotation transformation, which has the following form:

\[
p(X) = c_i x + c_j y + c_k z
\]

N is the number of RBF control points that are distributed around ship hull form, including the RBF fixed control points and the RBF movable control points, which determine the range and size of the deformation of hull surfaces. \( \phi \) is the radial basis function, which has many forms such as Gaussian spline function, thin plate spline function and Beckert Wendland C2 function. In this paper, the Beckert Wendland C2 function is chosen as the radial basis function. It can guarantee the matrix of the linear system is symmetric positive definite. There many numeric methods to solve this type of linear system equation. The r is the support radius.

\[
\phi(||s||) = \begin{cases} 
(1 - ||s||/r)^2 ||s|| / (r + 1) & 0 \leq ||s|| \leq r \\
0 & ||s|| \geq r 
\end{cases}
\]

The coefficients of \( \lambda_i \) and \( c_i \) is determined by the interpolating condition:

\[
S(X_i) = f_i, \quad i = 1, 2, ..., N
\]

where \( f_i \) is the displacement of the control points. To obtain the ultimate solutions, additional constraints conditions are imposed.

\[
\sum_{j=1}^{N} \lambda_j p(X_j) = 0
\]

Then by solving the following linear system:

\[
\begin{bmatrix} M & q \end{bmatrix} \begin{bmatrix} \lambda \\ c \end{bmatrix} = \begin{bmatrix} f \\ 0 \end{bmatrix}
\]

where \( \lambda = [\lambda_1, \lambda_2, ..., \lambda_N]^T \), \( c = [c_1, c_2, c_3, c_4]^T \), \( f = [f_1, f_2, ..., f_N]^T \), the matrix M and q are defined as:

\[
M_{i,j} = \phi(||X_i - X_j||), \quad i,j = 1, 2, ..., n
\]

\[
q = \begin{bmatrix} 1 & 1 & ... & 1 \end{bmatrix}^T
\begin{bmatrix} x_1 & x_2 & ... & x_n \\ y_1 & y_2 & ... & y_n \\ z_1 & z_2 & ... & z_n \end{bmatrix}
\]
The unknown coefficients are obtained. It is notable that the support radius \( r \) in Beckert Wendland \( C^2 \) function has a great impact on deformation range and solution efficiency. A smaller support radius can increase the efficiency of solving linear system but may lead to generate saddle-shaped surfaces. On the contrary, a larger support radius can achieve large deformation of hull surfaces. The support radius \( r \), which is twice of the maximum length of the Delaunay triangulation, is chosen in this paper according to the results obtain by Cheng et al (2018).

BULBOUS BOW GENERATION METHOD

In modern ship designs, bulbous bow has become a part of nearly all conventional ships. The bulbous bow influences the hydrodynamic performance of ship hull by redistributing the flow in the bow. A well designed bulbous bow can generate waves that interfere with the waves generated by hull, which weakens the wave height reducing wave-making resistance. The bulbous bow can increase the length of the flow and the flow separation can be prevented or delayed in this areas. The breaking waves also can be deflected. In general, the hydrodynamic performances of bulbous bow are the function of several non-dimensional form parameters. Many researches had been done to the design and optimization of bulbous bow (Perez et al, 2007; Huang-Kim and Yang, 2014; Wang, 2015; Yang-Huang and Wang, 2016). Traditionally, the bulbous bow is designed on basis of the several form parameters. When the form parameters are determined according to designer’s experiences or regression data, the bulbous bow can be built from sectional area curve to hull surfaces step by step (Perez et al, 2007). Compared with traditional method, it is more difficult to generate a bulbous bow for a hull without bulbous bow because it needs to achieve large deformation in the bow and still meet some geometric constraints and ensure the smoothness. A NURBS-based hull surface modification method combined with RBF method is used in this paper to the automatically generation and optimization of bulbous bow.

The Series 60 model is adopted here for the explanation of the flow of bulbous bow generation and optimization. Generally, it is divided into three steps to generate a practical bulbous bow (Huang-Kim and Yang, 2014; Yang-Huang and Wang, 2016). Firstly, make sure that the hull represented by NURBS surfaces has enough NURBS control points in the regions that are to be deformed, which allows for more flexible deformation. Distinguish the unchanged regions in hull surfaces with the regions that needed to be deformed. For the bulbous bow generation, only the regions in the bow will be deformed. Secondly, the NURBS control points of hull surfaces in the deformed region, which are all plotted as dot in Fig. 3, are divided into fixed RBF control points and movable RBF control points. The NURBS control points of the hull in the boundary that divide hull surfaces into changed and unchanged parts and the ship bottom, are chosen as fixed RBF control points to keep these NURBS controls points unchanged after deformation so that the original ship hull can be easily preserved. The green dots in Fig. 3 are the fixed RBF control points. The movable RBF control points are placed in the bow below the waterline, which are shown in red dot in Fig. 3. The displacement of movable control points depends on the length and depth of the bulbous bow that is to be generated. The selection of fixed and movable RBF control points is not unique and relies on the design requirements and designer’s experience. By solving the Eq. 14, the coefficients of RBF method are obtained and the displacement of the rest NURBS control points in deformed region shown as blue dot in Fig. 3 are calculated by Eq. 9. Then a bulbous bow is generated from Series 60 model, which is shown in Fig. 4.

After this step, the basic longitudinal profile of the bulbous bow is acquired. But the obtained bulbous bow may look like a blade, which is not practical in real life. Therefore, the third step is to remodel the bulbous bow generated above in term of its breadth. The process is mostly the same as the longitude formation. Then the initial bulbous bow is obtained, as it is shown in Fig. 5.

Fig. 3 NURBS control points to be deformed of Series 60 model in the bow and the distribution of fixed and movable RBF control points.

Fig. 4 Bulbous bow generated from Series 60 model by longitude formation.

BULBOUS BOW OPTIMIZATION

Through the longitudinal profile formation and transverse broadening, the Series 60 model with the initial bulbous is obtained. Then the hydrodynamic optimization of the initial bulbous bow is applied for the reduction of wave drag coefficient. The objective function in this paper is defined as:

\[
\min f_{\text{obj}} = C_w, \quad Fr = 0.27
\]

A NURBS-based hull surface modification method combined with RBF method is capable of achieving the large deformation of hull surfaces, which is suited for the generation of bulbous bow, as alluded to above. But this method has its disadvantages. A ship hull represented by the NURBS surfaces cannot be used as direct input for the hydrodynamic evaluation module based on NM theory, which requires that the hull surfaces should be represented by discrete meshes such as triangular panels. If the number of sample points is too many, it is time-consuming to generate discrete meshes for every hull form that is obtained by NURBS-based hull surface modification method. Therefore, in the optimization of bulbous bow, it is efficient to modify the bulbous bow based on hull meshes, which is applied in the present research. Firstly, the triangular meshes are generated from the hull with initial bulbous bow. To avoid generating skew meshes after the deformation of bulbous bow, which affects the computational accuracy by NMShip-SJTU solver, the regions that are to be deformed are refined properly.

Secondly, to change the form parameters of bulbous bow including the length, breadth, depth, and the longitudinal and lateral distribution of volume, two discrete mesh points are selected as the RBF movable control points. The \( P_1 \) plotted in red color is able to move in the \( x \) and \( z \) directions, which can change the length and depth of bulbous bow where the \( P_2 \) can move along the \( y \) direction to change the breadth of bulbous bow, which are shown in Fig. 5. The position of \( P_2 \) in the vertical direction has an effect on the shape of bulbous bow. The \( P_2 \) is
located in the medium so that an O type of bulbous bow is generated. The total design variables are three and the variation of design variables are shown in Table 2.

![Fig. 5 Distribution of design variables for bulbous bow optimization.](image)

**Table 2. Summary of design variables for Series 60 model**

<table>
<thead>
<tr>
<th>No.</th>
<th>Design Variables</th>
<th>Range</th>
<th>Optimal Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>P1-x</td>
<td>[0.52, 0.54]</td>
<td>0.54</td>
</tr>
<tr>
<td>2</td>
<td>P1-z</td>
<td>[-0.032, -0.016]</td>
<td>-0.029</td>
</tr>
<tr>
<td>3</td>
<td>P2-y</td>
<td>[0.0026, 0.0085]</td>
<td>0.0061</td>
</tr>
</tbody>
</table>

When the design variables and their variation range are confirmed, the sample points should be generated from the given design space. Then the hydrodynamic performances of candidate hull forms generated by hull surface modification method according to the sample points are evaluated by flow solver. It is unrealistic to evaluate all optional ship hull forms in design space. Therefore, the surrogate model is constructed to represent the relationships between the objective functions and the design variables, which can save computational costs and accelerate the optimization process. It is obvious that the accuracy of surrogate model become more precise with more sample points but increasing the computational times at the same time. So the Optimal Latin Hypercube Sampling method (OLHS) is adopted to generate sample points, which can guarantee that the distribution of sample points is orthogonal and uniform in the design space. The number of sample points here are 60. After the values of the objective function are obtained, the Kriging method is applied to construct surrogate model. The accuracy of surrogate model is directly influence the final optimal solution. Before the optimization process, the fidelity of surrogate model is validated by cross-validation method.

In the cross validation, 59 sample points are used to construct Kriging model, which is used to predict the value of objective function for the remaining point. Then the predicted value by Kriging model is compared with the corresponding value evaluated by NMShip-SJTU solver. It can be observed that the objective function values, namely the wave drag coefficient, estimated by the surrogate model have a good agreement with these corresponding values directly evaluated by the flow solver.

![Fig. 6 Cross-validation results of surrogate model](image)

**NUMERICAL RESULTS**

The comparison of the body plans and sheer plans between the initial hull without bulbous bow and the hull with optimal bulbous bow are shown in Fig. 7–8. It can be observed from Fig. 7–8 that the developed NURBS-based hull surface modification method can generate a practical bulbous bow for the Series 60 model. In addition, only the regions in the bow are deformed where the rest of hull surfaces remain unchanged.

![Fig. 7 Comparison of body lines between the initial and optimal hull forms](image)

**Fig. 8 Comparison of sheer lines between the initial and optimal hull forms**

The free surface elevation and distribution of pressure in hull surfaces calculated by NMShip-SJTU solver are compared between the initial hull without bulbous bow and the hull with optimal bulbous bow, which are shown in the Fig. 9–10, respectively.

![Fig. 9 Comparison of the free surface elevation between the initial hull and the optimal hull calculated by NMShip-SJTU solver](image)

The genetic algorithm is applied to search for the optimal solution of the objective function represented by surrogate model constructed above. Then the bulbous bow with optimal hydrodynamic performance is obtained. The optimal value of design variables obtained are listed in Table 2.

**NUMERICAL RESULTS**

The comparison of the body plans and sheer plans between the initial hull without bulbous bow and the hull with optimal bulbous bow are shown in Fig. 7–8. It can be observed from Fig. 7–8 that the developed NURBS-based hull surface modification method can generate a practical bulbous bow for the Series 60 model. In addition, only the regions in the bow are deformed where the rest of hull surfaces remain unchanged.
Fig. 10 Comparison of the pressure distribution around hull surfaces between the initial hull and the optimal hull calculated by NMShip-SJTU solver

It can be seen from the Fig. 9 that the free surface elevation of the optimal hull has a dramatically reduction in the bow compared with the initial hull without bulbous bow, which reduces the wave-making resistance. The hull surfaces are only deformed in the bow, therefore, the free surface elevation and the distribution of pressure remain nearly unchanged in the rest of areas. In order to verify and validate the hydrodynamic performance of the optimal hull form, the wave drag coefficients of the optimal hull are calculated at a range of speeds by NMShip-SJTU solver and are compared with the initial hull form and the hull form with initial bulbous bow, which is shown in Fig. 11.

Fig. 11 The wave drag coefficient curves of Series 60 model without bulbous bow, with initial bulbous bow, and with the optimal bulbous bow.

It can be observed from Fig. 11 that the optimal hull form has a reduced wave drag coefficients in most range of Froude numbers compared with the initial hull without bulbous bow. The percentage of wave drag coefficient reduction is shown in Table 3. The hull form with the optimal bulbous bow has a more than 20 percentages of reduction of wave drag coefficient at Fr =0.27 compared with the initial hull. In addition, the wet surface area and displacement of the hull with optimal bulbous bow are 1.6317 m² and 0.1222 m³, respectively.

Table 3. Wave drag coefficient reduction of Series 60 model without bulb, with initial bulb, with optimal bulb at Fr=0.27 predicted by low-fidelity NMShip-SJTU solver

<table>
<thead>
<tr>
<th></th>
<th>Fr = 0.27</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial bulb</td>
<td>-17.79 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optimal bulb</td>
<td>-21.36 %</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The NMShip-SJTU solver based on potential flow theory is used to evaluate the objective function during the optimization process due to its rapidity in computation speed. But the viscous influence of flow isn’t considered. It is necessary to further validate the hydrodynamic performance of the optimal hull form through high-fidelity CFD tool based on RANS method. In this paper, the in-house solver named naoe-FOAM-SJTU, which is developed on the basis of the open source CFD tool called OpenFOAM, is used to calculated the hydrodynamic performance of the initial hull and the optimal hull at Fr=0.27 in terms of model scale. The variation of the pressure drag, viscous drag, and total drag between the initial hull and optimal hull at Fr=0.27 is shown in Table 4.

Table 4. The variation of the pressure drag, viscous drag, and total drag coefficients between the initial hull and optimal hull at Fr=0.27 predicted by high-fidelity naoe-FOAM-SJTU solver

<table>
<thead>
<tr>
<th></th>
<th>C_p</th>
<th>C_v</th>
<th>C_t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial hull</td>
<td>1.3782e-3</td>
<td>3.0741e-3</td>
<td>4.4523e-3</td>
</tr>
<tr>
<td>Optimal hull</td>
<td>1.2251e-3</td>
<td>3.0594e-3</td>
<td>4.2845e-3</td>
</tr>
<tr>
<td>Variation</td>
<td>-11.11%</td>
<td>-0.48%</td>
<td>-3.77%</td>
</tr>
</tbody>
</table>

The pressure drag coefficient is reduced by 11.11 percentages where the total drag coefficient has a 3.77 percentage reduction.

To further analyze the results obtained by the high-fidelity naoe-FOAM-SJTU solver, the details of the flow field around hull are compared between the initial hull and the optimal hull.

Fig. 12 Comparison of the wave elevation on the free surface between the initial hull and the optimal hull predicted by naoe-FOAM-SJTU solver

Fig. 13 Comparison of the pressure distribution around hull surfaces between the initial hull and the optimal hull predicted by naoe-FOAM-SJTU solver

The wave elevation on the free surface of the optimal hull has notably reduction compared with initial hull, which is consistent with the results obtained by the NMShip-SJTU solver. During the optimization process, the most of computation time is using for the evaluation of objective functions by CFD tools. The NMShip-SJTU solver is suited for the optimization of ship hull form because it can catch the variation tendency of the hydrodynamic performance of candidate hull forms and is less time-consuming compared with high-fidelity CFD tools.

CONCLUSIONS
In the present study, a NURBS-based hull surface modification method combined with the RBF method is developed and integrated to the in-house solver named OPTShip-SJTU. It combines the advantages of the two methods. Due to the good mathematical properties of NURBS surface, the local large deformation of hull surfaces can be achieved by moving the NURBS control points. At the same time, the deformed regions can have a smooth connection with the unchanged parts. The radial basis function interpolation method is applied to move the NURBS control points of hull surfaces, which is able to reduce the number of design variables and meet the geometric constraints. To validate the feasibility of the developed method, the Series 60 model is chosen as parent ship and the wave drag coefficient is optimized through this method. Firstly, a bulbous bow is generated in the bow by the NURBS-based hull surface modification technique combined with RBF method including the longitude profile formation and transverse remodeling. Then the initial bulbous bow is optimized where the evaluation of objective function is calculated by fast solver based on NURBS control points of hull surfaces, which is able to reduce the number of design variables and meet the geometric constraints. To validate the feasibility of the developed method, the Series 60 model is chosen as parent ship and the wave drag coefficient is optimized through this method. Firstly, a bulbous bow is generated in the bow by the NURBS-based hull surface modification technique combined with RBF method including the longitude profile formation and transverse remodeling. Then the initial bulbous bow is optimized where the evaluation of objective function is calculated by fast solver based on NURBS control points of hull surfaces, which is able to reduce the number of design variables and meet the geometric constraints. To validate the feasibility of the developed method, the Series 60 model is chosen as parent ship and the wave drag coefficient is optimized through this method. Firstly, a bulbous bow is generated in the bow by the NURBS-based hull surface modification technique combined with RBF method including the longitude profile formation and transverse remodeling. Then the initial bulbous bow is optimized where the evaluation of objective function is calculated by fast solver based on NM theory. The obtained optimal bulbous bow has a superior hydrodynamic performance by reducing the wave elevation in the ship bow. The numerical results are further verified and validated by the high-fidelity solver, which proves that the developed method is an efficient and valid method for the hydrodynamic optimization of real life ship. In the future, the developed hull surface modification method will be applied to the hydrodynamic optimization of other standard ship model and further improved.

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