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Bow Optimization of A Polar Tanker Based on Approximate Technology

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ABSTRACT

The hydrodynamic performances in both of the ice area and the open water area should be considered in the design optimization of polar ship. In this study, the bow of a polar tanker is optimized to reduce the resistance in open water while the ice resistance is being kept. To solve the problem of consuming too much calculation time, the optimization method based on approximate technology is established. The parametric modeling method based on characteristic parameter is used to generate the parametric model of the bow. In approximate technology the uniform experimental design is improved by cutting method and genetic algorithm to improve the approximation accuracy. In optimization the resistance in open water is calculated by CFD numerical simulation based on viscous theory, and the ice resistance is predicted by discrete element method. After optimization, the resistance in open water of model ship and effective power of full scale ship are respectively decreased by 4%~6% and 7%~10% while the ice resistance is being improved, and the principal parameters, such as the displacement, almost keep the same.

KEY WORDS: Polar tanker; Bow optimization; Ice resistance; Resistance in open water; Approximate technology.

INTRODUCTION

Polar ship is the key equipment for shipping and resource exploitation in polar region. With the progress of the arctic route opening and the polar resource exploitation, many countries are focusing on the relevant key technology research and building a lot of polar ships.

As a primary technology for ship development, the ship design optimization is being widely studied. But there are few researches on design optimization of the polar ship recently. The optimization mostly focuses on the ship navigating in open water area. Peri, D. (2010), Jiankui Qian (2012), Zhailiu Hao (2015) et al. research the parametric modeling method, approximate technology, multi-objective optimization algorithm and multidisciplinary design optimization method to improve the hydrodynamic performance in open water. But for the polar ship, the related research mainly concentrates on ice resistance calculation. Shunying Ji

(2011), Konuk, I. (2009), Belytschko, T. (1999), Gürtner, A. (2008) et al. study the discrete element method (DEM), computational cohesive element method(CCEM) and finite element method (FEM) to improve the calculation accuracy of ice resistance. The researches on design optimization of polar ship are few. Kazuo Nozawa (2009) studies the parametric design method and optimizes the bulbous bow to improve the icebreaking ability.

The polar ships navigate not only in ice area, but also in open water area. So the hydrodynamic performances in both of the ice area and the open water area should be considered in the design optimization of these ships. In this study, the bow of a polar tanker is optimized to reduce the resistance in open water while the ice resistance is being kept. The optimization method based on approximate technology is established to obtain the optimized hull. Firstly the optimization process is established. Then the parametric modeling method based on characteristic parameter is used to generate the parametric model of the bow. After that, the approximate model of resistance in open water is established. In approximate technology, the uniform experimental design is improved by cutting method and genetic algorithm to improve approximation accuracy. In optimization process, the resistance in open water is calculated by CFD numerical simulation based on viscous theory, and the ice resistance is predicted by discrete element method. Based on the above works, the approximate model is optimized by multi-island genetic algorithm (MIGA) to obtain the optimized hull. Finally the resistances in open water and the ice resistances of the initial ship and the optimized ship are compared to verify the effectiveness of the bow optimization.

OPTIMIZATION MODEL

The optimization object is a polar tanker with ship length between perpendiculars 259.2m, breath 44.0m, draft 15.89m and volume 145663m^3. Its geometric shape is shown in Figure 1, and the optimization part is the bow. The optimization speed for resistance in open water is the design speed 15kn, and the design icebreaking speed is 2.54kn.

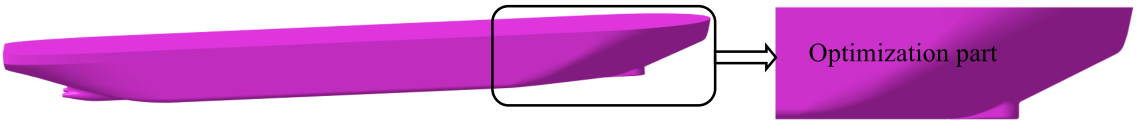


Figure 1. Hull geometry of the polar tanker

OPTIMIZATION METHOD

Optimization Process

To solve the problem of consuming too much calculation time, the optimization method based on approximate technology is established, and the corresponding optimization process is specified as follows. Step 1, the characteristic parameters are selected and their ranges are determined, then the bow of the polar tanker is parametric modeled. Step 2, the uniform experimental design is improved to generate a series of hulls. Step 3, the resistances in open water of these hulls are calculated. Step 4, the approximate model of resistance in open water is established by using neural network model. Step5, the approximate model is optimized by MIGA algorithm to obtain the optimized hull. Step6, the resistance in open water and ice resistance of optimized ship are predicted and verified. Step7, if the resistance is satisfied with design requirement, output the optimized hull, otherwise go back to step 1 to adjust the characteristic parameters and re-optimize the bow until the satisfied hull is obtained.

Parametric Modeling

The parametric modeling method based on characteristic parameter is used to generate the parametric model of the bow. Considering resistance in open water, ice resistance and smoothness of hull surface, 5 characteristic parameters shown in Figure 2 are selected to obtain the parametric model of the bow, which are water line curvature of forward shoulder, water line angle, curvature of bow section lines, stem angle and width of forward skeg. After the parametric model is generated, different bow lines can be obtained by changing the value of the 5 characteristic parameters.

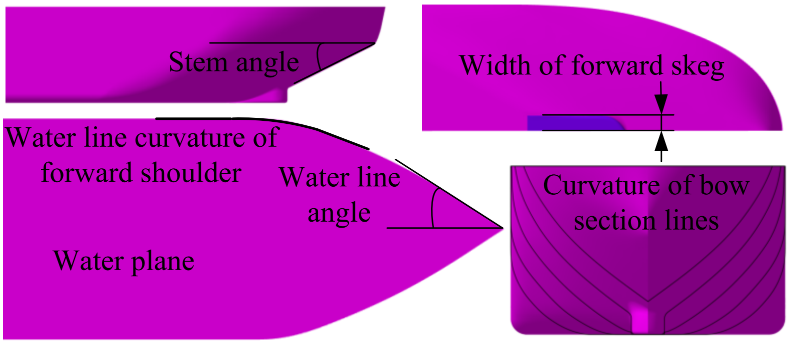


Figure 2. Characteristic parameters

In this optimization the following limiting conditions need to be considered for determining the ranges of characteristic parameters. (1) The ranges of water line angle and stem angle should be limited to keep the ice resistance. (2) The change rates of displacement and longitudinal center of buoyancy need to be less than 1%. (3) Considering the separation of crushed ice, the longitudinal projection contour of forward skeg should remain the same.

Approximate Technology

The parametric hull transformation and the calculation of resistance in open water consume too much time, which greatly influences the optimization efficiency and quality. Therefore, the approximate technology is introduced to generate approximate model for optimization.

The successful application of approximate model depends on its approximate accuracy, and the experimental design has great influence on the approximate accuracy. For this purpose, the uniform experimental design is chosen to generate the approximate model to improve approximate accuracy in this paper. As for the uniform experimental design, it is difficult to satisfy the requirement of uniformity and computational efficiency simultaneously in the present study, which restricts its application in engineering practice. So the cutting method and the genetic algorithm are introduced in this paper to solve this problem to efficiently generate the uniform experimental design with arbitrary number of variables and samples.

The uniformity measure of uniform experimental design in this study is the center deviation L_2- $CD_2(P_n)$ which has the expression:

$$CD_2\left(P_n\right)=\left[\left(\frac{13}{12}\right)^s-\frac{2^{s-1}}{n}\sum_{k=1}^{n}\prod_{i=1}^{s}\left(2+\left|x_{ki}-\frac{1}{2}\right|-\left|x_{ki}-\frac{1}{2}\right|^2\right)\right.$$
$$\left.+\frac{1}{n^2}\sum_{k,l=1}^{n}\prod_{i=1}^{s}\left(1+\frac{1}{2}\left|x_{ki}-\frac{1}{2}\right|+\frac{1}{2}\left|x_{li}-\frac{1}{2}\right|-\frac{1}{2}\left|x_{ki}-x_{li}\right|\right)\right]^{1/2} \quad (1)$$

Where $P_n = \{x_k = (x_{k1},...,x_{ks}), k = 1,...,n\}$ is the design matrix in the test area C^s, n is the number of samples, and s is the number of variables.

In uniform experimental design the U matrix is generated by good lattice point method in this paper. When sample number is even, the uniformity of the generated schemes is hard to meet the requirement. Therefore, the cutting method proposed by Changxing Ma (2004) is introduced in this paper to improve the uniformity, and the steps are as follows:

Step 1, for the uniform experimental design $U_n(n^s)$, select a prime p where $p>n$, and obtain the uniform experimental design $U_p(p^s)$ with the design matrix $P_u^{'} = \{c_1,...,c_s\}$ by good lattice point method. Step 2, denote $P_u^{'}$ as $C = (c_{ij})$, and reorder C according to the sample value in its lth column to generate the reordered matrix $C^{(l)} = (c_{kj}^{(l)})$ where $l = 1,...,s$. Step 3, for $m = 1,..., p$, $C^{(l,m)} = (c_{kj}^{(l,m)})$ is computed as follows:

$$c_{kj}^{(l,m)} = \begin{cases} c_{k+m-n-1,j}^{(l)} & m > n, k = 1,...,n, j = 1,...,s-1 \\ c_{k,j}^{(l)} & m \le n, k = 1,...,m-1, j = 1,...,s-1 \\ c_{k+p-n,j}^{(l)} & m \le n, k = m,...,n, j = 1,...,s-1 \end{cases} \qquad (2)$$

Step 4, for each m and l, a $C^{(l,m)}$ with n rows and s columns can be obtained, and the total number of $C^{(l,m)}$ is ns. The uniform experimental design $U_n(n^s)$ with the minimum CD_2 in the uniform experimental designs corresponding to all of the $C^{(l,m)}$ is expected.

The uniform experimental design can be obtained by the cutting method when the numbers of variables and samples are small. But as the numbers increasing, the computational efficiency will be reduced significantly. Actually, experimental design is an optimization problem with certain uniformity measure as the objective. So the genetic algorithm with great search ability is able to solve the computational efficiency problem.

The uniform experimental design $U_n(n^s)$ generated by genetic algorithm is executed in two steps. The first step is to generate $U_p(p^s)$ where p is prime. The U-type design with p rows and $p-1$ columns can be obtained by good lattice point method. Then the s columns from the $p-1$ columns with the minimum CD_2 are selected to generate $U_p(p^s)$. When executing genetic algorithm, there are s variables and the objective is CD_2. Each variable represents each column of the U-type matrix, and is natural number with the value from 1 to $p-1$. The second step is to select $U_n(n^s)$ in $U_p(p^s)$ by the cutting method. When executing genetic algorithm, there are two variables and the objective is CD_2. Both of the variables are natural numbers. One is related to the row of $U_p(p^s)$ with the value from 1 to p, and the other is related to the column of $U_p(p^s)$ with the value from 1 to s. By executing genetic algorithm two times, the uniform experimental design with arbitrary number of samples and variables is able to be generated efficiently.

In the bow optimization of polar tanker, comprehensively considering calculation work and approximate accuracy, 125 hulls are generated in this study, and their projection of 3 variables is shown in Figure 3.

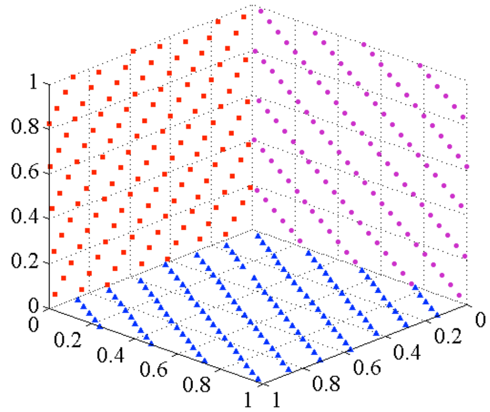


Figure 3. Projection of 3 variables

RESISTACE CLACULATION METHOD

The resistance in open water is calculated by CFD numerical simulation based on viscous theory, as is introduced by Chengsheng Wu (2010). The control equation is continuity equation and RANS equation, which are expressed as follows:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{3}$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\nu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] - \frac{\partial\left(\overline{u_i' u_j'}\right)}{\partial x_j} + f_i \tag{4}$$

The SST *k–ω* turbulence model is used to close the RANS equation. The free surface is captured by VOF (volume of fluid) method, which introduces volume fraction to simulate two or more kinds of fluids.

The ice resistance is calculated by discrete element method. The level ice unit is simulated by particle parallel bond model, and the hull structure is expressed by triangular element with certain arrangement mode. The parallel bond model sets an elastic bond disk between two particle bond units, and the disk can transfer force and moment between the two units, including tension, shear, bending moment and torque. The ice resistance is able to be obtained by using contact model to calculate contact force and simulating interaction of friction and collision between ship and ice or among ice units.

The particle unit force can be divided into normal force and tangential force. The normal force F_n and the tangential force F_s are defined as:

$$F_n = K_n x_n - C_n x_n \tag{5}$$

$$F_s^* = K_s x_s - C_s x_s \quad F_s = \min\left[F_s^*, sign(F_s^*)\right]\mu F_n \tag{6}$$

Where K_n, C_n, x_n and x_n are the stiffness coefficient, damping coefficient, deformation and strain rate of particle in the normal direction, K_s, C_s, x_s and x_s are the corresponding parameters in the tangential direction, and μ is friction coefficient.

The frost action among particles is realized by establishing the parallel bond model. The force

$\overline{F}_i$ and moment $\overline{M}_i$ on the bond disk are:

$$\overline{F}_i = \overline{F}_i^s + \overline{F}_i^n \quad \overline{M}_i = \overline{M}_i^s + \overline{M}_i^n \tag{7}$$

Where $\overline{F}_i^n$ and $\overline{F}_i^s$ are the normal and tangential force, $\overline{M}_i^n$ is the torque, and $\overline{M}_i^s$ is the moment on the bond disk.

OPTIMIZATION RESULT AND ANALYSIS

Optimization Result of Resistance in Open Water

The optimization objective is the model resistance in open water at the design speed 15kn. After the approximate model of resistance in open water is established, the optimized ship is obtained by optimizing this approximate model with MIGA algorithm, which has 5 islands with 20 populations in each island and 200 generations.

According to CFD calculation, the comparison of resistances between initial ship and optimized ship is shown in Table 1, where R_m is the model resistance in open water, R_s and P_E are the resistance and effective power of full scale ship, $CHAR_m$ is the change rate of R_m, and the $CHAP_E$ is the change rate of P_E. As for the optimized ship, its R_m and P_E are respectively decreased by 4%~6% and 7%~10%, and especially at the design speed its R_m and P_E are respectively decreased by 5.08% and 8.27%.

Table 1. Comparison of total resistance and effective power

V_s (kn)	Fr	R_m (N)			R_s (kN)		P_E (kW)		
		Initial ship	Optimized ship	$CHAR_m$	Initial ship	Optimized ship	Initial ship	Optimized ship	$CHAP_E$
10	0.099	23.38	22.40	-4.18%	567.5	528.0	2919.2	2715.8	-6.97%
12	0.123	32.98	31.63	-4.08%	811.5	757.0	5009.1	4672.8	-6.71%
14	0.143	44.55	42.64	-4.30%	1116.5	1038.5	8040.5	7478.9	-6.98%
15	0.153	51.16	48.57	-5.08%	1295.8	1188.7	9998.2	9171.7	-8.27%
16	0.163	59.29	56.08	-5.42%	1535.6	1402.3	12638.7	11541.5	-8.68%
18	0.184	77.02	72.09	-6.40%	2062.1	1855.1	19093.3	17176.3	-10.04%

The ship length, breath and draft of the optimized ship are not changed, and the other principal parameters, such as the displacement and the longitudinal center of buoyancy, almost keep the same with the initial ship. After optimization, it is obtained that: (1) the water line angle is increased; (2) the stem angle is decreased; (3) the transition between bow and midship area is more smooth; (4) as for the forward skeg, its longitudinal projection contour remains the same and its width is decreased; (5) the radian of section lines become larger when approaching the midship; (6) and as the waterlines going down, its entrance radian is growing.

Figure 4 compares the wave-making between initial ship and optimized ship. It is observed from the figures that the wave-making of optimized ship is obviously improved.

Optimization Result of Ice Resistance

After the optimization of resistance in open water, the ice resistance of the optimized ship is verified by discrete element method. The resistances when breaking level ice with thickness

1.60m at 3 speeds are predicted and shown in Table 2 and Figure 5, where V_S represents ship speed and R_I represents ice resistance. The collision of level ice with ship hull is shown in Figure 6. It is obtained that at low speed the ice resistances of optimized ship and initial ship are similar, and as the speed increasing the ice resistance of optimized ship is being obviously improved. At design icebreaking speed 2.54kn, the ice resistance of optimized ship is decreased by 3.74%. So the ice resistance is improved and the precondition of the bow optimization in this study is satisfied.

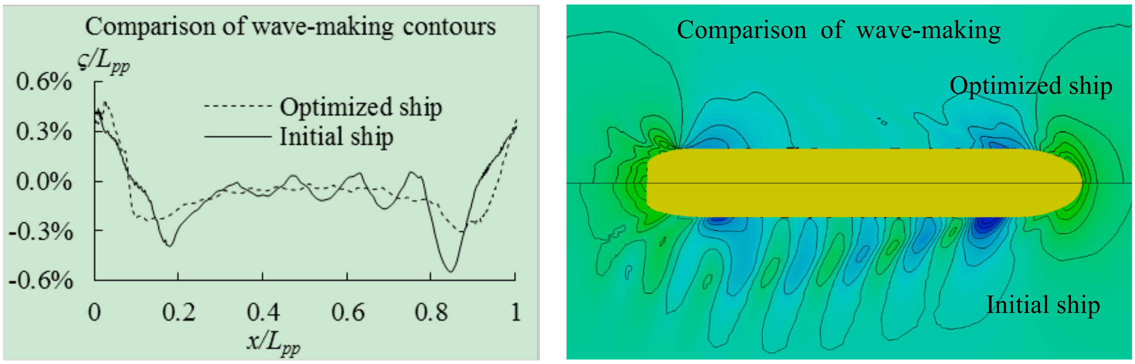
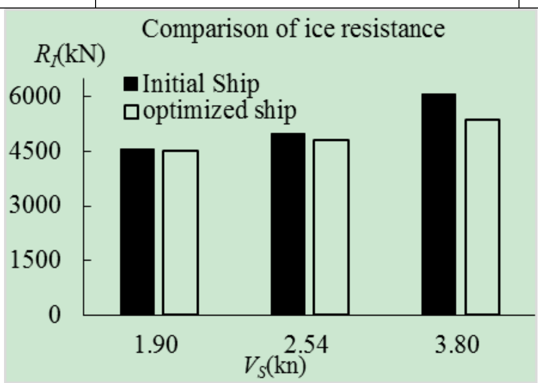


Figure 4. Comparison of wave-making

Table 2. Comparison of ice resistance result

Speed (kn)	Ice resistance of initial ship (kN)	Ice resistance of optimized ship (kN)	Change rate
1.90	4558.9	4510.3	-1.07%
2.54	5004.5	4817.2	-3.74%
3.80	6074.0	5374.4	-11.52%



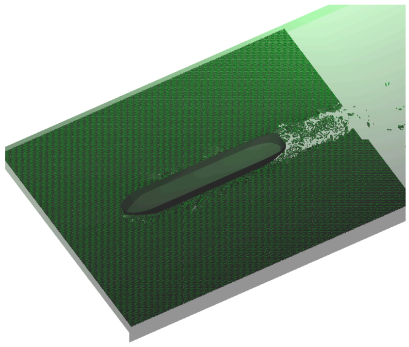


Figure 5. Comparison of ice resistance

Figure 6. Collision of level ice with ship hull

CONCLUSIONS

The bow of a polar tanker is optimized to reduce the resistance in open water while the ice resistance is being kept. To solve the problem of consuming too much calculation time, the optimization method based on approximate technology is established to obtain the optimized hull. The water line curvature of forward shoulder, water line angle, curvature of bow section lines, stem angle and width of forward skeg are selected as the characteristic parameters to generate the parametric model of the bow. In approximate technology, the uniform experimental design is improved by cutting method and genetic algorithm to improve the approximate accuracy. In optimization, the resistance in open water is calculated by CFD numerical simulation based on viscous theory, and the ice resistance is predicted by discrete element method. After optimization, the resistance in open water of model ship and effective power of full scale ship are respectively decreased by 4%~6% and 7%~10% while the ice resistance is being improved, and the principal parameters, such as the displacement, almost keep the same.

Having high optimization efficiency by introducing approximate technology, and being able to optimize the detail flow field based on CFD simulation, the optimization method established in this study can be effectively used for polar ship optimization in engineering practice.

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