Multi-objective Optimization Design of KCS Based on Seakeeping Performance

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ABSTRACT
Seakeeping is a key standard to examine whether a ship has good performance in waves. Ship hull forms can significantly affect the motion behavior in waves and the influences vary a lot under different wave conditions. Therefore, it is necessary to conduct the multi-objective optimization design of ship hull based on seakeeping performance in different waves. In the present work, the KRISO Container Ship (KCS) is considered as a parent ship. The hull form is globally deformed. The main principal parameters are constrained within a certain range. The heave and pitch motions in the typical head wave condition are used as objective functions. The whole optimization process is implemented based on in-house solver OPTShip-SJTU. It turns out that OPTShip-SJTU has a very practical application in the aspect of multi-objective optimization of ship seakeeping performance based on CFD.

KEY WORDS: Seakeeping performance; CFD; OPTShip-SJTU solver; multi-objective optimization

INTRODUCTION
The pros and cons of seakeeping is one of the important indicators to measure the performance of a ship. In most cases, ships sail in the waves. In particular, some offshore engineering vessels, such as marine drilling vessels often sail in heavy sea condition. Seakeeping directly affects the navigation, safety and comfort performances of a ship. Ships’ severe motions have a series of detrimental impact on the ship, including the safety and efficiency of crew and various equipment and so on. Therefore, ship preliminary design must consider the seakeeping performance. Seakeeping is determined not only by the external marine environment, but also closely related with the ship’s main particulars and shape. Under a given marine environment, it may be considered to guide ship design optimization with the aim of improving seakeeping performance.

Ship optimization design is mostly based on the rapidity performance of ships in still water (Campana et al, 2006; Zhang et al, 2015; Huang & Yang, 2015; Liu et al, 2016; Wu et al, 2017). In recent years, some scholars also consider seakeeping performance in ship optimization design. At first, some seakeeping performance indicators is only as constraints (Harries, 2001), and later also taken as objective functions. Peri and Campana (2003a) optimized the hull shape line with the total resistance and ship's heave and pitch peaks as three objective functions. D. Peri and Campana (2003b) established a ship optimization model to minimize the total resistance and the maximum velocity and acceleration of different locations at two different speeds and three different sea states. Peri et al (2004) improved wave-making resistance, heave and pitch peak and the vortex around the top of the sonar at a single speed. Boulougouris et al (2006) considered the total resistance and maximum vertical motion at the center of gravity to create a multi-objective optimization problem. Diez et al (2015) presented recent research conducted within the NATO RTO Task Group AVT-204 "Assess the Ability to Optimize Hull forms of Sea Vehicles for Best Performance in a Sea Environment ", with the goal of reducing drag and improving seakeeping performance. The parent ship was the DTMB 5415. Six research teams including ECN, TUHH, NTUA, INSEAN, ITU and UI were involved in this ship optimization problem considering the two speeds, the head and oblique waves, the vertical acceleration and the rolling angle of the bow and the total resistance. The results were compared and analyzed. The most promising hull was with the resistance improved by nearly 10% and the seakeeping 9%, respectively. Qiu et al (2011) implemented integrated optimization design on the iSight platform for the ship drag/seakeeping performance of the 46000 DWT oil tanker. The total resistance per displacement of the unit and peak pitching and pitch peak were taken as the objective functions of ship optimization; Yang et al (2011) selected four objective functions of significant pitch angle, the acceleration, the number of slamming per hour and significant roll angle, improving seakeeping performance of a fishing vessel. The four objective functions of the optimized hull were increased by 2.32%, 7.17%, (-0.13%) and 9% respectively. Bagheri et al (2014) optimized the Wigley ship model with the heave and pitch peaks as the objective functions. Seakeeping in researches above was almost evaluated by strip theory. Also, some scholars (Kim et al, 2010; Wu et al, 2016) optimized ship seakeeping just evaluated by simple empirical formulas. These evaluation methods are fast but low-fidelity.

This paper aims for hull form optimization of KCS, to improve
seakeeping performance based on CFD by modifying hull form lines, using in-house solver, OPTShip-SJTU. Before the optimization process, several benchmark cases are calculated to verify the present CFD solver naoe-FOAM-SJTU in the prediction of ship motion in waves. The initial hull form is modified globally by Shifting method and locally by FFD method to attain a series of new hull forms. Through the numerical simulation of a ship sailing in the given wave situation by naoe-FOAM-SJTU (Ye et al, 2012; Shen et al, 2012), the heave and pitch motions of the sample ships generated by the optimal Latin hypercube sampling (OLHS) approach are all calculated. The surrogate model is used to express the relationship between the design variables and objective functions, namely the given design space by Kriging method. In the design space, the heave and pitch motion are taken as two objective functions, using NSGA-II algorithm (Deb, 2000; Deb et al, 2003) to search for the optimal solutions of this multi-objective optimization problem (See in Fig. 1). Finally, the differences between the initial hull form and the selected optimal hull forms are analyzed in detail.

Fig. 1 The flow chart of the multi-objective optimization design of hull form.

KCS MULTI-OBJECTIVE OPTIMIZATION

KCS is a standard ship model (Fig. 2) and chosen as the initial hull form in the paper. Its main hull form parameters and wave condition suffered are shown in Table 1, 2. In this paper, the selection of wave conditions refers to standard experimental set conditions proposed by T2015 Workshop (Simonsen, 2008).

Fig. 2. Ship hull form of KCS.

Table 1. The main particulars of the initial hull form (in scale)

<table>
<thead>
<tr>
<th>Item</th>
<th>Ship model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length between perpendiculars (Lpp) /m</td>
<td>6.070</td>
</tr>
<tr>
<td>Breadth moulded (B) /m</td>
<td>0.850</td>
</tr>
</tbody>
</table>

Table 2. The given head wave conditions from experiments

<table>
<thead>
<tr>
<th>Wave condition</th>
<th>Wave height/m</th>
<th>Wave length/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>0.062</td>
<td>3.949</td>
</tr>
<tr>
<td>C2</td>
<td>0.078</td>
<td>5.164</td>
</tr>
<tr>
<td>C3</td>
<td>0.123</td>
<td>6.979</td>
</tr>
<tr>
<td>C4</td>
<td>0.149</td>
<td>8.321</td>
</tr>
<tr>
<td>C5</td>
<td>0.196</td>
<td>11.840</td>
</tr>
</tbody>
</table>

The optimization aims at improving seakeeping performances, and is formulated as

Min \( f_1(x), f_2(x) \)

Where \( x \) is the design variable vector, \( f_1 \) is the normalized amplitude of heave motion under the selected C3 condition, \( f_2 \) the normalized amplitude of pitch motion under the selected C3 condition.

\[
f_1 = \frac{A_{H_{\text{pitch}}}}{A_{H_{\text{pitch}}}}
\]

\[
f_2 = \frac{A_{P_{\text{pitch}}}}{A_{P_{\text{pitch}}}}
\]

with \( A_{H_{\text{pitch}}} \) is the amplitude of heave motion of the initial hull form, \( A_{P_{\text{pitch}}} \) is the amplitude of pitch motion of the initial hull form in head wave. The wave conditions correspond to C3 in Table 2.

Notably, here only ship motion in one kind of wave conditions (C3) are chosen as the objective functions in the optimization design, considering the computational cost. However, the motion response of the optimal ship will be further compared to that of the initial ship under five different wave conditions, to make sure that the improvement of seakeeping performance.

WAVE GENERATION (INLET BOUNDARY)

The wave is generated by modification of the velocity boundary condition and the phase boundary condition. In this study, Stokes 2nd wave theory was adopted in the generation of the wave according to the calculated wave cases. The equation of Stokes 2nd wave theory is expressed as

\[
\eta = \frac{H}{2} \cos \delta + \frac{H}{8} \left( \frac{\pi H}{\lambda} \right) \frac{\cosh kd}{\sinh \lambda} (\cosh 2kd + 2) \cos 2\delta
\]

In which, \( \eta \) is the wave elevation of free surface, \( H \) wave height of the generated wave, \( \delta = x - \alpha t + \phi \) the phase, \( T \) wave period, \( d \) the water depth of the computational domain (here it is considered as deep water),
\( \omega \) the wave angular frequency, \( k \) the wave number, and wave dispersion relation is \( \omega^2 = gk \tanh(kd) \).

In this study, the calculation domain is set as a wavelength upstream of the ship, three wavelengths downstream of the ship, and five wave probes at five different positions. The calculation depth is a length of a ship. The grid is about 2 million according to the results of grid convergence.

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**NUMERICAL CALCULATION OF KCS SHIP MOTION**

Before optimization, the motion of the parent ship in waves must be simulated accurately to ensure the numerical calculation and optimization results. In this paper, the heave and pitch motion of KCS ship in five wave conditions are numerically simulated and compared with the experimental test.

Here, the heave and pitch motions are evaluated by naoe-FOAM-SJTU solver, developed based on the open source CFD toolbox, OpenFOAM. An incompressible RANS method with two-phase interface is applied to simulate the viscous flow around ship in regular head waves. A six-degrees-of-freedom (6DoF) module is implemented to predict the motion of ship, which is handled by a dynamic deforming mesh method solving a Laplace equation.

**DESIGN MODIFICATION METHOD**

In this paper, two approaches, shifting method (Kim, 2010; Wu, 2017) and FFD method (Wu, 2016,2017), are employed to modify the geometry of hull form globally and locally. The combination of the two approaches makes the deformation more flexible and only a few design
variables involved.

In shifting method, hull forms are represented by using the sectional area curves. A new hull shape can be derived by adjusting the longitudinal spacing of the transverse sections to suit the new curve of sectional area, which is obtained by modifying the initial one through a shape function.

The expression of the new sectional area curve is developed as follows:

\[ f^n(x) = f^o(x) + g(x, \alpha_1, \alpha_2) \]  \hspace{1cm} (5)

where the shape function \( g \) is defined as:

\[
g = \begin{cases} 
\alpha_1 \left[ 0.5(1 - \cos 2\pi \frac{x - \alpha_2}{\alpha_2 - x_1}) \right]^{0.5}, & x_1 \leq x \leq \alpha_2 \\
\alpha_2 \left[ 0.5(1 - \cos 2\pi \frac{x - \alpha_1}{\alpha_1 - x_2}) \right]^{0.5}, & \alpha_2 \leq x \leq x_2 \\ 
0, & \text{elsewhere} 
\end{cases}
\]  \hspace{1cm} (6)

in which \( f^n(x) \) represents the expression of new sectional area curve while \( f^o(x) \) is corresponding to the initial one; \( g(x) \) is the shape function with four arguments; \( x_1 \) and \( x_2 \) control the range of area needed to be modified; \( \alpha_1 \) determines the slope of the new sectional area curve, and \( \alpha_2 \) denotes the location of the fixed station. An application of shape function \( g \) is carried out and the initial curve of sectional area is modified partly (Fig. 8).

Bernstein polynomial, \( l, m, n \) are the numbers of the control points along the \( x \)-axis, \( y \)-axis, \( z \)-axis direction, respectively. Through changing the movable number, direction and displacement of the control points, the different ship surfaces can be easily obtained.

**ESTABLISHMENT AND VALIDATION OF SURROGATE MODEL**

Because of high computational expense of CFD and a large number of hull form cases to evaluated, a surrogate model is applied to the optimization design of hull forms. 35 sample points of hull forms are wisely chosen by the OLHS (optimal latin hypercube sampling) method and their corresponding performances (two objective functions) are directly evaluated by naoe-FOAM-SJTU solver. A surrogate model expressing the relationship between each objective function and three design variables are built based on the Kriging method. In the following optimization process, the objective function values of any individual of ship hull form are predicted by these surrogate models, rather than directly and repeatedly by the entire CFD method. It greatly reduces the optimization time. So, before the optimization, the fidelity of surrogate models needs to be validated, generally by the cross-validation method (Fig. 9). In the cross validation, each sample point is evaluated from the Kriging surrogate model that is constructed by the other 34 sample points. It can be observed that the objective function values \( f^c, i = 1, 2 \) estimated by the surrogate model show a good agreement with these values \( f^e, i = 1, 2 \) directly evaluated by the entire CFD method.

**THE WHOLE SETTINGS OF THE OPTIMIZATION**

The whole settings of this optimization problem are shown in Table 3 at length, such as the optimization algorithm, the design variables, the constraints, etc.

<table>
<thead>
<tr>
<th>Type</th>
<th>Definition</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Initial hull</strong></td>
<td>KCS</td>
<td></td>
</tr>
<tr>
<td><strong>Objective functions</strong></td>
<td>( f_1 = \frac{A_{h}\text{ave}}{A_{h}\text{ave}} ) Fr=0.261 U=2.017m/s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( f_2 = \frac{A_{p}\text{ick}}{A_{p}\text{ick}} )</td>
<td></td>
</tr>
<tr>
<td><strong>Design variables</strong> (dimensionless parameters)</td>
<td>( \alpha_1 ) [-0.03:0.03] Parameters in shifting method</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \alpha_2 ) [-0.03:0.03]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \Delta x ) (Variable1) [-0.01:0.015] Displacement in ( x ), ( y ), ( z ) direction in the fore-part region, respectively in FFD method</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \Delta y ) (Variable2) [-0.007:0.007]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \Delta z ) (Variable3) [-0.014:0.014]</td>
<td></td>
</tr>
</tbody>
</table>
RESULTS OF OPTIMIZATION

At each iteration of the procedure, the objective functions of 200 individuals (new ships) are quickly evaluated by surrogate models. 30% of individuals scoring the best are migrated. 80% of individuals will swap their genes between each other. Finally, the objective functions are not reduced until 100 iterations. That is to say, through the optimization procedure mentioned above, the Pareto front (a series of optimal solutions) is attained. All of optimal solutions reflect the trade-offs between two conflicting objectives (heave and pitch motions). First, the difference of hull lines between the initial hull form and the optimal hulls are intuitively observed (Fig.10). Obviously, the two new bulb bows are upturned and widens in the transverse direction. For the ship Optimal-1, its stern is slightly different from the initial hull, while the stern of the ship Optimal-2 is quite fatter than that of the initial hull.

Fig. 10 Comparisons of hull lines between the optimal and initial hull forms

The relative changes of the heave and pitch motions of two hull forms are shown in Table 4. All of two objective function values slightly decreases. The seakeeping performance of the optimal hull forms have been improved.

Table 4. Relative changes of two objective functions by surrogate models

<table>
<thead>
<tr>
<th>Term</th>
<th>Relative changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal-1</td>
<td></td>
</tr>
<tr>
<td>Amplitude of heave motion</td>
<td>-9.94%</td>
</tr>
<tr>
<td>Amplitude of pitch motion</td>
<td>-1.69%</td>
</tr>
<tr>
<td>Optimal-2</td>
<td></td>
</tr>
<tr>
<td>Amplitude of heave motion</td>
<td>-9.60%</td>
</tr>
<tr>
<td>Amplitude of pitch motion</td>
<td>-2.89%</td>
</tr>
</tbody>
</table>

VALIDATION OF THE OPTIMIZATION RESULTS

In order to validate the optimal hull form obtained in this study, the optimal hull form is simulated by naoe-FOAM-SJTU and further compared to the initial hull form in detail.

According to Table 5, the heave and pitch motions of optimal hulls are calculated by naoe-FOAM-SJTU based on RANS method, and the comparison between optimal and initial hulls verifies the real improvement of the seakeeping performance., in agreement with the results by surrogate model.

Table 5. Relative changes of two objective functions by naoe-FOAM-SJTU

<table>
<thead>
<tr>
<th>Term</th>
<th>Relative changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal-1</td>
<td></td>
</tr>
<tr>
<td>Amplitude of heave motion</td>
<td>-8.34%</td>
</tr>
<tr>
<td>Amplitude of pitch motion</td>
<td>-2.10%</td>
</tr>
<tr>
<td>Optimal-2</td>
<td></td>
</tr>
<tr>
<td>Amplitude of heave motion</td>
<td>-9.21%</td>
</tr>
<tr>
<td>Amplitude of pitch motion</td>
<td>-3.08%</td>
</tr>
</tbody>
</table>
The time histories of heave and pitch motions of the initial hull form and optimal hull forms are shown in Figs.11~12, which points out the success of the selected optimal hulls. From RAO results of heave and pitch motions (Figs 13~14), heave and pitch motions of the optimal hull form both decreases. It demonstrates that the multi-objective optimization design in the paper is successful and useful, which has some help to the design of hull form.

CONCLUSIONS

In this paper, KCS was successfully modified by Shifting method globally and FFD method locally, a series of hull forms generated, thus obtaining a greater design space. Then, the seakeeping performance of these hull forms were evaluated by naoe-FOAM-SJTU solver, a high-fidelity solver based on CFD method, which ensured the following surrogate models built more accurately. The use of the surrogate model greatly decreased computational expense, which made the evaluation of objective functions during the optimization process faster and accurate enough. So, the optimization based on CFD became feasible. Moreover, about the seakeeping performance, considering the computational expense, just one wave condition was selected. The motion amplitude response of optimal ships in five wave conditions was also calculated to ensure the improvement of seakeeping performance. All over the optimization process was finished by in-house solver OPTShip-SJTU applicable for a multi-objective hull form optimization problem.

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REFERENCES


