AN INNOVATIVE HULLFORM DESIGN TECHNIQUE FOR LOW CARBON SHIPPING
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ABSTRACT
Combining modern Computational Fluid Dynamics (CFD) evaluator with optimization method, a new approach of hullform design for low carbon shipping is presented. Using the approach, the designers may find the minimum of some user-defined objective functions under constrains. An example of the approach application for a surface combatant hull optimization is demonstrated. In the procedure, the Particle Swarm Optimization (PSO) algorithm is adopted for exploring the design space, and the Bezier patch method is chosen to automatically modify the geometry of bulb. The objective function, the total resistance is assessed by RANS solvers. It’s shown that the total resistance coefficient of the optimized design is reduced by about 6.6% comparing with the original design. The given combatant design optimization example demonstrates the practicability and superiority of the proposed approach for low carbon shipping.

Keywords: Hull design optimization, low carbon shipping, CFD techniques, PSO algorithm

NOMENCLATURE
CFD Computational Fluid Dynamics
Cp Dynamic pressure coefficient
C_T Total resistance coefficient
E Error
F Objective Function
Fr Froude Number
L Ship’s length
PSO Particle Swarm Optimization
RANS Reynolds-Averaged Navier-Stokes
Re Reynolds Number
SBD Simulation Based Design
V Ship’s speed
v_x, v_y, v_z Design variables
x,y,z Coordinate system, with x aft, y to starboard, and z upward, coordinate of a field point
δ Variation
Δ Ship’s displacement

1. INTRODUCTION
In recent years, there is growing concern about the environment and climate change. In 2007, international shipping contributed approximately 3% of global anthropogenic CO2 emissions. It’s forecasted that, by 2020, the amount of greenhouse gas emissions for the global shipping industry will increase by 75% and the fuel will be consumed 400 million tons. With the implementation of low-carbon economy, shipping industry is facing a tough task of carbon emissions reduction.

To complete carbon emissions reduction of shipping industry, it’s firstly necessary to analyze the distribution rules of carbon emissions during the whole life cycle of ship, discriminate the key link and influence factors of producing carbon emissions and draw up the effective measure of carbon emissions reduction. Ship is a complex product. The whole life cycle of ship can be divided into four stages including processing and transportation of materials required for ship construction, ship building, ship operation and ship disassembling. For example, the statistics of carbon emissions of an 180,000 tons bulk carrier during the whole life cycle is presented in Figure 1.

Figure 1: Carbon emissions statistics during the whole life cycle of a ship

It’s shown in figure 1 that the proportion of carbon emissions in the operation stage is the most and about 94.92% of the total amount. Obviously, it is necessary to restrict carbon emissions during the operation stage of ship if we want to reduce carbon emissions of the whole life cycle. Because it’s burning is the main reason of CO2 emissions. Therefore, reducing the fuel oil consumption becomes the key to control carbon emissions of ship in the whole life cycle.

Currently, there are two possible pathways to reduce and control carbon emissions of ship. One is using new energy technology, such as solar energy, sail, et al. But some new energy technology is far away from practical application in projects and can not put into practice immediately. Another is reducing the fuel oil consumption, i.e., reducing the total resistance of ship. For this purpose, the new hullform design technique is developed for low carbon shipping. Using the technique, the hullform with optimal hydrodynamic performance will be devised.

In common practice, the ship design involves several cycles, in which the desk studies and model basin experiments are coordinated. The solutions coming from the design department are tested in the model basin, and then the experimental results drive the new solution to be produced, until the designer’s requirements are fulfilled. These design
methods can only choose a relative best one in the limited cases. The potential of design is far from being fully extracted. And the traditional design methods has decades of practical application in the mainstream ship, almost reach the extreme on improving its hydrodynamic performance, which is difficult to get breakthrough.

CFD numerical simulation method and optimization algorithms can be combined together into what is known as Simulation Based Design (SBD) techniques. Using the new techniques the designers may find the minimum of some user defined objective functions under different constrains. For low carbon shipping design, the applications of the techniques can obviously reduce the total resistance and fuel consumption in shipping process, and accordingly reduce the carbon emissions during the ship's whole life cycle.

In recent years, computational tools for hydrodynamic optimization of ships have been developing at a fast speed. The rapidly growing amount of research devoted to hydrodynamic optimization of hullform design adopting SBD techniques. Pinto et al. (2007) solved a shape optimization of a container ship using deterministic particle swarm optimization algorithm. The amplitude operator on peaks of heave and pitch motion response of the ship advancing at fixed speed in head seas was reduced. DTMB 5415 has been recently taken as a test case by some optimization studies. The bow bulb redesign was undertaken by Newman et al (2002) using sensitivity analysis and complex variable finite difference approach. The method used a RANS solver to minimize sonar dome vortices neglecting free surface effects. A finite-difference gradient-based approach was followed by Tahara et al. (2000, 2004) for stern and sonar dome optimization using RANS (with free surface effects) and exploring the advantages of high performance parallel FORTRAN. In a series of papers, Peri and Campana (2001, 2003a, 2003b) investigated a variable-fidelity approach to speed up the optimization process using free surface RANS in single- and multi-objective problems, while Peri and Campana (2003c, 2004, 2005) developed a global optimization algorithm, applied to the solution of the same test, and the experimental campaign carried out to assess the success of the optimization. These papers cited above witness that the SBD techniques (CFD-based hullform design) are receiving growing consideration in the ship hydrodynamics design field.

In this paper, the fundamental elements of SBD techniques are analyzed and alternative components are described. And then, the application of the approach in the hullform optimization design is illustrated through a practical example in detail. The results confirm the applicability and superiority of the SBD techniques to low carbon shipping design problems.

2. BASIC ELEMENTS OF KNOWLEDGE-BASED HULLFORM DESIGN ENVIRONMENT

To develop Simulation-Based Design techniques for shape design, three main components must be built and are common among many different applications (Fig. 2). First, an optimization technique that can be used to minimize the objective functions under given constraints. Second, a hull geometry modeling and modification technique that provides the necessary link between the design variables (and their variations) and the deformation of the body shape. And third, a CFD solver used as analysis and evaluation tools to return the value of the objective function and of functional constraints. The functional components needed to support SBD techniques are briefly analyzed and described in the following.

![Figure 2: CFD-based hullform design optimization environment](image)

2.1 OPTIMIZERS

Optimization technique is used for exploring the hullform design space and obtaining the optimal solution of optimization problem. Therefore, selecting what kinds of optimization algorithms, so that it can quickly and accurately search the optimal solution in the design space, is one of the research focuses for hull optimization design.

The traditional gradient-based optimization algorithms are widely applied, mainly due to their good convergence properties and computational efficiency when a relatively small number of variables are considered. However, due to nonlinear constraints, non-convex feasible design spaces are quite common in practical problems as well as multimodality of the objective functions, the local optimization algorithms might be trapped in the local minima and be inefficient in solving these problems. With the increase of computer power and the development of efficient global optimization algorithms, in recent years non-gradient-based algorithms have attracted much attention. Global optimization algorithms provide several advantages over local optimization algorithms. They are generally easy to program and to parallelize, do not require continuity in the problem definition, and are
generally better suited for finding a global, or near global, solution. Accordingly, the author suggests that the global optimization algorithms should be chosen in solving practical engineering optimization problems.

2.2 GEOMETRY AND GRID MANIPULATOR

An accurate and effective hull geometry modeling and modification technique plays an important role in the CFD-based hullform design optimization. Flexibility of the geometry modeling and modification technique may greatly affect the freedom of an optimizer to explore the design space. Specifically, it needs to ensure several aspects. First of all, only a small number of parameters, i.e., design variables, are required for the hull geometry variation to minimize the number of objective function evaluations. Second, large variation of hull forms can be obtained to allow for sufficient free-form design, i.e., to produce different type of hullforms. Third, modified portion can join the original design smoothly without discontinuities when only a part of the hull needs to be optimized. Finally, practical hullform can be preserved and various geometrical constraints can be easily implemented in the optimization process.

With regard to grid manipulation, once the hull geometry is modified, the volume grid is adjusted accordingly. In order to reduce the numerical error caused by meshing format, the grid dimension and topology structure of the different hulls geometric surface should assure consistency.

2.3 CFD SOLVERS

CFD solvers used as analysis and evaluation tools to return the values of the objective function and functional constraints. The accuracy of CFD solvers has a large impact on the practical implementation and often also on the success of the optimization process. Generally speaking, before the design optimization is carried out, the validation and verification of CFD solvers should be first performed. At the same time, the improvement obtained by design optimization should larger than the numerical noise of CFD solvers.

The CFD solvers used in hullform design optimization studies consist of RANS solvers or potential flow solvers. Potential flow solver is very highly efficient in evaluating the objective function, but its accuracy is very poor. On the contrary, RANS solvers is very good accuracy, but its efficiency is low. How to guarantee the accuracy of the objective function solved, and meanwhile improve CFD solver efficiency, is the emphasis of shape optimization design research currently.

3. EXAMPLE AND APPLICATIONS

In this section the applications are presented, in order to demonstrate the applicability of SBD techniques to the low carbon shipping design. Realistic geometrical constraints have been adopted in the problem’s formulation.

The geometry of the David Taylor model No. 5415 is selected as the base configuration in the optimization process. The modifiable region is only the foremost part of the ship, i.e., the bow and the bulb (see figure 3). There is a large experimental database for model 5415, due to an international collaborative study on experimental/numerical uncertainty assessments.

The example of DTMB5415 is a difficult one, because the optimizer has reduced freedom and hence expected improvements are small. The problem is solved for the bare hull.

3.1 DEFINITION OF THE DESIGN PROBLEM

3.1 (a) Objective Functions

As stated above, the most effective way to reduce the carbon emissions of ship in the whole life cycle is to reduce the fuel consumption during ship voyage, namely reduce the total resistance of ship. Hence, the objective function $F$ to be minimized is the total resistance coefficient, $C_T$, of the model advancing in calm water at a speed of $Fr=0.28$. This condition corresponds to $Re=1.67\times10^7$ when using a reference length of 5.72 m, which is the length of the ship's model adopted in the model experiment.

3.1 (b) Modification of Hull Bulb Geometry

Bezier Patch approach is adopted to deform the hull bulb geometry, which is to superimpose a Bezier patch on the original bulb that gradually reduces to zero perturbation when approaching the boundary of the patch itself, to join the unmodified portion of the hull shape smoothly (details in Peri and Campana (2001)). A Bezier surface is controlled by a fixed number of control points. The control points of the Bezier surface are assumed as design variables of the optimization problem. Above mentioned requirements (Section 2.2) can be easily satisfied.

In figure 4, the geometry of bulb can be modified in all the directions by using three different Bezier patches — $x$, $y$, $z$ — one for each coordinate.
The five design variables are used for the parameterization deformation: one variable \( v_{x1} \) are used to modify the shape in longitudinal direction \((x)\), three variables \( v_{y1}, v_{y2}, v_{y3} \) are used to modify the shape in the lateral direction \((y)\), and one variable \( v_{z1} \) are used to modify the shape in vertical direction \((z)\).

Geometrical constraints are imposed on the design variables, on the bulb and on the displacement of the ship. The definition of constraints is given in Table 1. The volume of the bulbs is constrained, and cannot vary of more than the 1.5% of its initial value. These limitations are necessary because the sonar must fit in the new bulb too.

### Table 1: Constraint conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 0 / L \leq v_{x} \leq 0.08 / L )</td>
<td>( -0.05 / L \leq v_{z} \leq 0.10 / L )</td>
</tr>
<tr>
<td>( -0.05 / L \leq v_{y} \leq 0.10 / L )</td>
<td>( -0.08 / L \leq v_{y} \leq 0 / L )</td>
</tr>
<tr>
<td>( -0.10 / L \leq v_{y} \leq 0.10 / L )</td>
<td>( 0.985 \Delta \leq \Delta^* \leq 1.015 \Delta )</td>
</tr>
</tbody>
</table>

### 3.1 (d) Evaluation of Objective Functions

For an advanced fluid dynamic redesign of some part of an existing shape, accurate analysis tools are necessary for guiding the optimizer toward improved solutions. This is true also for ship redesign and the most advanced analysis tools available today to design engineers are RANS solvers. The degree of reliability of free-surface RANS code has constantly matured during the last 10 years.

In this paper, CFD tool adopted solves RANS equations for unsteady, three-dimensional incompressible flow by using the higher-order upwind difference method, the discrete formulation by a finite volume technique. And the free-surface is captured by adopting VOF method. The k-omega turbulence model is used to close of equations. The grids are multi-block-structured with hexahedral elements (on the order of 1,140,000 grid points, see figure 5).

![Figure 5: Computation region and hull surface mesh](image)

Before the design optimization is carried out, the validation study is first performed for the original hullform DTMB 5415. Table 2 shows the comparisons of experimental measurements (Lei, 2008) and numerical predictions for the total resistance coefficients at the different speed, where the total resistance coefficients are obtained using...
the RANS approach. It can be seen from Figure 4 and Table 2 that the total resistance coefficients are in consistent agreement with the experimental measurements (Bias errors within 3%). Table 2 also suggests that the CFD tool can predict the total resistance with reasonable accuracy. Therefore, the CFD tool based on the RANS approach is well suited for the hydrodynamic optimization of the hullform.

Table 2: Computational and experimental results of the total resistance coefficients for the original hullform.

<table>
<thead>
<tr>
<th>Fr</th>
<th>V(m/s)</th>
<th>Re(10^6)</th>
<th>C_T (10^-3)</th>
<th>E(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15</td>
<td>1.124</td>
<td>6.41</td>
<td>3.867</td>
<td>3.933</td>
</tr>
<tr>
<td>0.21</td>
<td>1.573</td>
<td>8.96</td>
<td>3.855</td>
<td>3.945</td>
</tr>
<tr>
<td>0.23</td>
<td>1.873</td>
<td>10.67</td>
<td>3.962</td>
<td>4.049</td>
</tr>
<tr>
<td>0.28</td>
<td>2.097</td>
<td>11.95</td>
<td>4.125</td>
<td>4.207</td>
</tr>
<tr>
<td>0.33</td>
<td>2.472</td>
<td>14.09</td>
<td>4.436</td>
<td>4.563</td>
</tr>
</tbody>
</table>

Figure 6: Comparison of the total resistance coefficients between computational and experimental results for the original hullform.

3.1 (e) Optimization Algorithms

In this paper, the Particle Swarm Optimization (PSO) algorithm is adopted for the optimizer. The PSO algorithm is a recent addition to the list of global search methods. Since it was originally introduced (Kennedy, 1995), the PSO algorithm has been studied by many authors (Eberhart, 2001, Campana, 2006, 2009, Sheng-zhong, 2010).

The swarm strategy simulates the social behavior of a set of individuals (particles) which share information among themselves while exploring the design variables’ space. In the basic PSO method each particle has its own memory to remember the best places that it has visited, whereas the swarm has a global memory to remember the best place ever visited. Moreover, each particle has an adaptable velocity to move itself across the design space. According to these principles, each particle investigates the search space analyzing its own travel experience and that of the other members of the swarm. Therefore, PSO algorithm can obtain the global optimal solution of the optimization problem.

3.2 DESIGN OPTIMIZATION RESULTS

The optimization processes ended with final geometries that clearly display some common geometrical trends. A careful analysis of the geometry shape (Fig.7) shows:

1) The relevant difference is the extension of the bulb in the forward (x) direction, about 10% ahead with respect to the total length of the bulb itself.
2) A reduction of the maximum width (y) of the bulb is reduced by about 13%.
3) A trend to uplift of the bulb in the upward (z) direction.
4) In addition, a very slight change of the wetted surface area and the displacement are shown in Tab.3 (-0.5% and -0.4%, respectively).

The numerical results for the objective function show that the SBD techniques are able to identify improved designs with lower total resistance with respect to the original Model 5415. Comparisons of the total resistance coefficients between the original and optimized hullforms at the different speed are shown in table 4. Reductions of the total resistance coefficients with respect to the original hull are also reported in Fig.8 as a function of the Froude number (values below 0% represent improved performance). At the design speed (Fr=0.28) the reduction of the total resistance coefficient is about 6.6% for the optimized hullform, while the numerical noise are clearly smaller than this value. It may be of interest to look at off-design conditions too: in the entire speed range, a maximum reduction of about 7.4% is obtained at Fr=0.21.

As shown in Figs.9 and 10, the computed wave patterns also reflect the improved resistance. The optimized hullform display remarkably reduced bow wave amplitudes. Furthermore, the steepness of the first wave crest and the first trough are also observably reduced. Improvements are also found in the pressure distribution (see Figs.11 and 12).

From the above analysis, the success of the optimization process is confirmed. This is very large improvement in the resistance performance of ship, considering the small modifications allowed and the good initial performances of the original hull. And it indicates that the SBD techniques are very attractive for low carbon shipping design.
Table 3: Comparison of main parameter between the original and optimized hullform.

<table>
<thead>
<tr>
<th>Type</th>
<th>Unit</th>
<th>Optimized</th>
<th>Original</th>
<th>δ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wetted Surface Area</td>
<td>m^2</td>
<td>4.835</td>
<td>4.861</td>
<td>-0.5%</td>
</tr>
<tr>
<td>Displacement</td>
<td>m^3</td>
<td>0.547</td>
<td>0.549</td>
<td>-0.4%</td>
</tr>
</tbody>
</table>

Table 4: Comparison of the total resistance coefficients between the original and optimized models.

<table>
<thead>
<tr>
<th>Fr (10^-1)</th>
<th>Computation results</th>
<th>Reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Optimized</td>
<td>Original</td>
</tr>
<tr>
<td>0.15</td>
<td>3.716</td>
<td>3.867</td>
</tr>
<tr>
<td>0.21</td>
<td>3.569</td>
<td>3.855</td>
</tr>
<tr>
<td>0.23</td>
<td>3.690</td>
<td>3.962</td>
</tr>
<tr>
<td>0.28</td>
<td>3.851</td>
<td>4.125</td>
</tr>
<tr>
<td>0.33</td>
<td>4.238</td>
<td>4.436</td>
</tr>
</tbody>
</table>

Figure 8: Resistance coefficients reduction (%) as a function of the Froude number for the optimized hullform (Error bars show the errors range between the computational and experimental results for original hullform).

Figure 9: Comparison of wave contours between the original and optimized hullform.

Figure 10: Comparison of wave profiles between the original and optimized hullform (y / L = 0.082).


4. CONCLUSIONS

The innovative hullform design techniques (SBD) for low carbon shipping are briefly introduced. The hydrodynamic ship design problem is solved, and optimization results have shown improvements in the objective function (the total resistance of the ship at model scale). This is a very valuable result, considering the small modifications allowed and the good initial performances of the original model. And it demonstrates the applicability and superiority of the hullform design techniques for low carbon shipping.

REFERENCES


