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An overview of simulation-based hydrodynamic design of ship hull forms*

Chi YANG, Fuxin HUANG
Center for Computational Fluid Dynamics, George Mason University, Fairfax, Virginia, USA,
E-mail: cyang@gmu.edu

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Abstract: This review paper presents an overview of simulation-based hydrodynamic design optimization of ship hull forms. A computational tool that is aimed to accomplishing early-stage simulation-based design in terms of hydrodynamic performance is discussed in detail. The main components of this computational tool consist of a hydrodynamic module, a hull surface modeling module, and an optimization module. The hydrodynamic module includes both design-oriented simple CFD tools and high-fidelity CFD tools. These integrated CFD tools are used for evaluating hydrodynamic performances at different design stages. The hull surface modeling module includes various techniques for ship hull surface representation and modification. This module is used to automatically produce hull forms or modify existing hull forms in terms of hydrodynamic performance and design constraints. The optimization module includes various optimization algorithms and surrogate models, which are used to determine optimal designs in terms of given hydrodynamic performance. As an illustration of the computational tool, a Series 60 hull is optimized for reduced drag using three different modification strategies to outline the specific procedure for conducting simulation-based hydrodynamic design of ship hull forms using the present tool. Numerical results show that the present tool is well suited for the hull form design optimization at early design stage because it can produce effective optimal designs within a short period of time.

Key words: simulation based design, ship hull form optimization, radial basis function, NURBS, hydrodynamics

Introduction

Hydrodynamic design of ships involves several stages, from preliminary and early-stage design to late-stage and final design. Hydrodynamic optimization is an important aspect of ship design. The computational fluid dynamics (CFD) based simulation tools can thus be used for evaluating the hydrodynamic performance of a design, or design alternatives during a design process.

In order to compare the merit of different designs quantitatively, the multi-objective functions that measure ship hydrodynamic performances are defined. These objective functions can be evaluated using CFD-based simulation tools for a given design, i.e., a hull form associated with a set of design parameters/variables. An optimal hull form that exhibits the best hydrodynamic performance can then be obtained via an optimization technique. Therefore, the simulation-based hydrodynamic design/optimization tool usually consists of a CFD module that can be used to compute the flow field and evaluate the objective functions, a hull surface modeling module that can be used to produce hull forms via given sets of design parameters/variables, and an optimization module that can be used to minimize the objective functions under given constraints.

Preliminary and early hydrodynamic design requires the evaluation of large number of objective functions during iterative procedures. The use of high fidelity models in design optimization, especially at early design stage, can be prohibitively expensive. In order to reduce the computational cost and still being able to rank different designs, it is essential to have computational tools that account for essential (but not necessarily all) relevant physics, and are highly efficient (with respect to CPU and user input time) and robust. Thus, linear potential flow assumptions may be in order for this stage of the design. As the design progresses, the level of physical realism needs to be upgraded, leading to Euler, RANS, and perhaps VLES computations for the final stage of the design. Therefore, it is necessary to develop both potential-flow

* **Biography:** Chi YANG, Female, Ph. D., Professor

based simple CFD tools and Euler/RANS/Navier-Stokes based high-fidelity CFD tools. These different CFD tools can be used at different stages of the design. The simple CFD tools can be used to evaluate the hydrodynamic performance, such as drag and sea-keeping, in the optimization process and the high-fidelity CFD tools can be used for the validation of the hydrodynamic performance of the final optimal hull forms obtained.

In order to perform simulation-based hydrodynamic design optimization of ship hull forms, it is very important to develop accurate and effective hull-surface representation and modification techniques to ensure: (1) Only a small number of parameters (design variables) are required to represent an existing hull form or produce a new hull form from scratch, thus minimizing the number of objective function evaluations, (2) Large variation of hull forms can be obtained by modifying given parameters (design variables), thus producing different type of hull forms, (3) Modified region can join the original design smoothly without discontinuities when only a part of the hull can be modified, (4) Practical hull form (both three-dimensional fairness and manufacture practicability) can be preserved and various geometrical constraints can be easily implemented in the optimization process.

Various optimization techniques can be adopted to minimize the objective functions. It is essential to include optimization techniques that are capable of finding local and/or global minimum for either single objective or multi-objective functions. These optimization techniques can be integrated into the optimization module. A suitable optimization technique can be selected from the optimization module to meet design needs.

In summary, the simulation-based hydrodynamic design/optimization of ship hull forms generally requires the following steps: (1) define an initial hull form with a set of design parameters/variables using hull surface modeling technique, (2) simulate the flow for the given hull form using CFD tools and evaluate the objective functions in terms of the flow solutions obtained, (3) minimize the objective functions using a optimization technique and update the design variables. Steps (1) to (3) are repeated until the solutions are converged, thus generating an optimal hull form with the best hydrodynamic performance. It is clear that extensive computing time is required to conduct simulation-based hydrodynamic design/optimization of ship hull forms if the flow for the given hull form is simulated by high-fidelity CFD tools during the iterations.

With the rapid development of computer hardware and numerical techniques in recent years, CFD-based computational tools have become more and more popular in analyzing hydrodynamic performance of ships. Some of these tools have been used to conduct hull form optimization studies[1-15], which have demonstrated that CFD-based hydrodynamic design optimization is extremely valuable. However, most of these tools cannot be used in the early-stage design of ship hull forms because they are very computing intensive, and hard to use for non-CFD experts. An efficient and effective simulation-based computational tool for the early-stage design of ship hull forms has been developed by the authors and their colleagues over the years[10,12,13,16-28]. An overview of this integrated computational tool and its application to the innovative hydrodynamic design of ship hull forms at the early-stage design are presented in details in this review paper.

The main components of this simulation-based hydrodynamic design and optimization tool consist of a hydrodynamic module, a hull surface modeling module, and an optimization module. The hydrodynamic module includes both design-oriented simple CFD tools and high-fidelity CFD tools. These integrated CFD tools are used for evaluating hydrodynamic performances at different design stages. The hull surface modeling module includes various techniques for ship hull surface representation and modification. This module is used to automatically produce hull forms or modify existing hull forms in terms of hydrodynamic performance and design constraints. The optimization module includes various optimization algorithms and surrogate models, which are used to determine optimal designs in terms of given hydrodynamic performance.

Many ship hull geometry modeling techniques have been reported in the literature[29-39] for the representation and modification of hull forms. These modeling techniques can be classified into two categories: conventional modeling and parametric modeling[29]. Conventional modeling techniques build on a low-level definition of geometry. For example, points are used to define curves, and curves are used to define surfaces. NURBS representation of the hull surface can be regarded as one of the conventional modeling techniques of the hull form, and some of the NURBS' control points can be taken as design variables for hull form modification in the CFD-based hydrodynamic optimization of the hull form. Although conventional modeling techniques offer the great flexibility with regard to geometry and topology, special cares are necessary to ensure the generation of the reasonable and practical hull forms if conventional modeling techniques are used for the hull form optimization. In addition, the conventional modeling of the hull form requires a large number of design variables. Parametric modeling techniques, on the other hand, build on high-level entities. These entities are called form parameters in geometric modeling. The major advantage of parametric modeling techniques is that small to intermediate modifications can be produced very efficiently and only a small number of design variables are required. However, the parametric modeling of the hull sur-