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Hydrodynamic Optimization of a Modern Container Ship using Variable Fidelity Models

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ABSTRACT

This paper presents a practical hydrodynamic optimization tool for the design of a modern container ship. In stead of using complex and computationally expensive CFD solvers with standard optimization methods, the present tool adopts the variable fidelity method that uses lower-fidelity models and a scaling function to approximate the higher-fidelity models to reduce computational cost. The method aims to maximize the use of lower-fidelity, cheaper models in iterative procedures with occasional, but systematic, recourse to higher-fidelity, more expensive models for monitoring the progress of the algorithm. The method is globally convergent to the solution of the original, high-fidelity problem. For purposes of illustration, the potential flow solvers with nonlinear and linear free surface boundary conditions are used as high-fidelity model and lower-fidelity model, respectively, in the present hydrodynamic optimization tool to determine the optimal hull form of a modern container ship for a given speed with displacement constraint.

KEY WORDS: Hydrodynamic optimization; Container ship; Variable fidelity model; Potential theory; High fidelity solver; Lower-fidelity solver.

INTRODUCTION

Hydrodynamic optimization is an important aspect of ship design. In order to perform hydrodynamic design optimization, an objective function that compares the merit of different designs quantitatively needs to be defined. This objective function depends on design variables, and the changes in flow variables due to them. The aim is then to minimize (or maximize) this objective function subject to PDE (Partial Differential Equations that govern the flow) constraints, geometry constraints, and physical constraints.

The CFD-based hull-form hydrodynamic optimization consists of CFD solver/solvers that can be used to compute the flow field and evaluate the objective function and its gradient if required by the optimization technique, hull geometry modeling and modification that are linked to the design variables, optimization technique that can be used to minimize the objective function under given constraints. While CFD based hull-form optimization is not routinely used for ship design, applications of CFD tools to hydrodynamic optimization mostly for reducing calm-water drag and wave patterns have been reported in a significant number of studies. These studies attest to a rapidly growing interest in hydrodynamic optimization (e.g., Janson and Larsson, 1996; Tahara and Himeno, 1998; Hino, 1999; Percival et al., 2001; Peri et al., 2001; Peri and Campana, 2003; 2005; Yang et al., 2000; 2002; 2008; Harries et al., 2004; 2007; Tahara et al., 2006a;b; Zalek et al.,2006; Hochkirch and Fassardi, 2007; Kim et al., 2008). The CFD solvers used in these studies consist of RANS solvers or potential flow solvers with various approximations.

As computational capabilities continue to increase, hydrodynamic performance of ships can be predicted by computational models of high physical fidelity or numerical accuracy, such as Euler/RANS/Navier-Stokes equations or these based on fine computational meshes. Unlike final design analysis, hydrodynamic design optimization requires the evaluation of large number of objective functions during iterative procedures. Therefore, the use of high fidelity models in design optimization, especially at early design stage, can be prohibitively expensive. On the other hand, the use of lower-fidelity models alone does not always guarantee the improvement for high fidelity design.

The efforts to reduce the computational cost using approximation methods have been continued in engineering design for a long time. Variable fidelity optimization is one of the approximation methods to reduce the computational cost (e.g. Gano, 2005). The method aims to maximize the use of lower-fidelity, cheaper models in iterative procedures with occasional, but systematic, recourse to higher fidelity, more expensive models for monitoring the progress of the algorithm. The method is globally convergent to a solution of the original, high fidelity problem. In this study, the variable fidelity optimization is employed for the hull form optimization problem by using trust region and first order multiplicative scaling model. As an illustration, the CFD solvers based on potential flow theory with nonlinear and linear free surface boundary conditions are used as high-fidelity model and lower-fidelity model, respectively. Specifically, the high-fidelity nonlinear potential flow solver is based on Rankine-source panel method, and the fully nonlinear free surface boundary conditions are satisfied at the exact free surface position (Raven 1996; Choi et al. 2001). The lower-fidelity linear potential flow solver is based on Neumann-Michell (NM) theory (Yang et al., 2007a;b). The computer code based on NM theory is very robust and highly efficient. The CPU time for evaluating the flow about a ship hull that is approximated by 10,000 panels is approximately 10 seconds per Froude number using an Intel Pentium 4 Processor PC (Yang et al., 2007a;b).

In addition to the CFD solvers and optimization techniques, hull geometry modeling and modification that are linked to the design variables are also the important part of the hydrodynamic optimization of hull forms. Many hull geometry modeling techniques have been developed over decades. Harries et al. (2004) analyzed various modeling techniques and divide them into two categories: conventional modeling and parametric modeling. Conventional modeling techniques build on a low level-definition of geometry. For example, points are used to define curves; curves are used to define surfaces. Conventional modeling techniques offer great flexibility with regard to geometry and topology. Parametric modeling techniques, on the other hand, build on high-level entities. These entities are called form parameters in geometric modeling. The most prominent advantage of parametric techniques is that small to intermediate modifications can be produced very efficiently. The parametric modeling of the hull form requires few numbers of design variables. Both conventional modeling and parametric modeling of the hull forms are implemented.

For purposes of illustration, the present study considers a simple hydrodynamic optimization problem: minimization of the wave drag of a modern container ship for a given speed with displacement constraint. As the focus of this study is on the optimization technique using variable fidelity model, the parametric modeling of the hull form is adopted.

DESCRIPTION OF VARIABLE FIDELITY OPTIMIZATION (VFO)

The efforts to reduce the computational cost using approximation method have been continued in engineering design optimization for a long time. As one of the approximate methods, the variable fidelity optimization method has been applied in various application areas, such as structural optimization, aerodynamic optimization, and multidisciplinary optimization (e.g. Barthelomy and Haftka, 1993; Peri and Compana, 2005; Alexandrov et al, 2000; Gano, 2005).

This approximation method is realized using a metamodel. Another optimization technique that makes a metamodel is response surface method. The response surface method is a type of optimization method that applies an optimization technique to the objective and other functions (Myers and Montgomery, 1995). Variable fidelity method uses a function similar to a response surface. In original response surface method, a sampling of high fidelity calls is needed to produce a low fidelity surrogate which approximates the high fidelity model. In variable fidelity method, only one high-fidelity function and gradient evaluation are required to make a scaling function. The high fidelity model is approximated using the lower-fidelity models and the scaling function. So, variable fidelity method can further reduce the computational cost than the original response surface method (Alexandrov et al., 2000; Gano, 2005).

In this research, variable fidelity method is used to reduce the computational cost associated with the evaluation of high fidelity flow simulations in the hydrodynamic optimization of hull forms. Fig. 1 shows the conceptual distinction between the conventional optimization and the variable fidelity optimization. The conventional optimization is shown on the left, in which the analysis results are provided to the optimizer directly with the objective function. The variable fidelity optimization is shown on the right, in which the results from both lower-fidelity and high-fidelity analysis are used to build a function for the local approximations to feed the optimizer. The variable fidelity method attempts to build a scaling function that is usually the first- or second-order Taylor series to match the result of the lower-fidelity model to the high-fidelity model. The method provably converges to the solution of the more expensive models with substantially less calls to the high-fidelity model than that required if optimization is done solely using the high-fidelity model. The trust region management scheme is used for the proof of convergence.

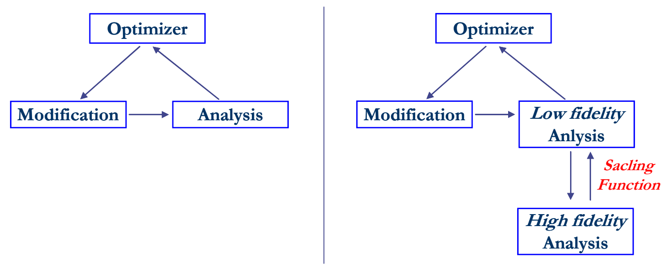

Fig. 1: Conventional optimization (left) and variable fidelity optimization (right).

Scaling Function

The scaling function was adopted for matching the lower-fidelity model to the high-fidelity model. Generally, two kinds of scaling functions have been used. One is multiplicative scaling function and the other is additive scaling function (Chang et al., 1993; Gano, 2005). In this paper, the multiplicative scaling function is used. The scaling ratio of the high fidelity model to the lower-fidelity model can be described as:

$$f_{high}(x) = \beta(x) f_{low}(x) \tag{1}$$

where $f_{high}(x)$ and $f_{low}(x)$ are objective functions evaluated using high-fidelity and lower-fidelity models, respectively, and $\beta(x)$ is the scaling function, and x is the design point associated with design variables. In the *n-th* step design, $\beta(x_n)$ is obtained as follows:

$$\beta(x_n) = f_{high}(x_n) / f_{low}(x_n) \tag{2}$$

where x_n is the design point corresponding to the design variables obtained at the *n-th* step. Using the first-order Taylor series expansion, the scaling function at any design point can be approximated as

$$\tilde{\beta}(x) = \beta(x_n) + \nabla\beta(x_n)^T (x - x_n) \tag{3}$$

Therefore, Eq. (1) can be rewritten as

$$f_{high}(x) \approx f_{scaled}(x) = \tilde{\beta}(x) f_{low}(x) \tag{4}$$

$f_{scaled}(x)$ is the scaled objective function used in this study as the approximation to the high-fidelity objective function.

Trust Region Management

In order to guarantee the convergence of the variable fidelity optimization, a trust region model management strategy is employed

(Rodrguez et al, 2000; Conn et al, 1988). This strategy provides a means for managing the allowable move limits adaptively in the approximate design space. A trust region ratio monitors how well the approximation matches the high fidelity design space. The trust region ratio ρ_n is calculated at the new candidate design point x_n^* as follows:

$$\rho_n = \frac{f_{high}(x_n) - f_{high}(x_n^*)}{f_{scaled}(x_n) - f_{scaled}(x_n^*)} \quad (5)$$

where $f_{high}(x_n)$ and $f_{high}(x_n^*)$ are the objective functions evaluated for the original design point and candidate design point at the *n-th* step, respectively, using high-fidelity model; $f_{scaled}(x_n)$ and $f_{scaled}(x_n^*)$ are scaled objective functions evaluated for the original design point and candidate design point at the *n-th* step, respectively, using lower-fidelity models described in Eq. (4).

It should be noted that by definition $f_{scaled}(x_n) \approx f_{high}(x_n)$ because the scaled lower-fidelity model matches the high-fidelity model for a given design point. The trust region ratio is therefore the ratio of the actual change in the function to the predicted change of the function by the scaled lower-fidelity model.

If ρ_n is near one, the approximation is quite good. If ρ_n is near zero, the approximation is not so good, but it can still capture the minimization trend. The design point is a worse design if ρ_n is negative. In this case the design point is rejected, the trust region size is reduced and the algorithm returns to the previous step.

Variable Fidelity Model Algorithm

The algorithm of the variable fidelity optimization (Gano 2005) can be described as follows:

STEP 1: At the starting design point x_0, the objective function is evaluated using both high- and lower-fidelity models, respectively, to obtain

$$f_{high}(x_0),\ f_{low}(x_0) \quad (6)$$

STEP 2: The gradient of the objective for both high- and lower-fidelity models is evaluated at the current design point x_n to obtain

$$\nabla f_{high},\ \nabla f_{low} \quad (7)$$

STEP 3: A scaling model is constructed to insure the matching between different fidelity models. This model can be based on the first order multiplicative scaling model described by

$$\tilde{\beta}(x) = \beta(x_n) + \nabla\beta(x_n)^T (x - x_n) \quad (8)$$

STEP 4: The lower-fidelity model scaled with the scaling model constructed in Step 3 is optimized. The optimization problem solved in this step is:

$$\text{Minimize: } f_{scaled}(x_n) \quad (9)$$
$$\text{Subject to: } g(x_n) \le 0$$
$$x_l \le x \le x_u$$

where $g(x)$ is given constrain, and x_l is lower bound and x_u is upper bound. The choice of optimizer is based on preference. The Sequential Quadratic Programming (SQP) is used in this study. SQP is one of the gradient based optimization techniques. It is fast and efficient at providing solution to local optimization problem (e.g. Vanderplatts 1984).

STEP 5: The trust region ratio is evaluated at the new candidate point x_n^*. If ρ_n is negative, the trust region size is reduced and the algorithm returns to Step 4. If ρ_n is positive, the trust region is adjusted and the algorithm proceeds to STEP 6.

STEP 6: Check the convergence condition. If the convergence test is true, then the final design is found. Otherwise, the algorithm returns to STEP 2. In this study, convergence is determined by the following stopping criterion:

$$f_{high}(x_n) - f_{high}(x_n - 1) < \varepsilon_f \quad (10)$$
$$\|x_n - x_{n-1}\| < \varepsilon_x$$

where ε_f and ε_x are tolerances supplied by the user, and n is the current iteration counter.

HULL FORM MODELING AND PARAMETRIC MODIFICATION

Choice of the hull-form modification function is important in optimization. The function must have sufficient generality for the desired hull form modifications. It should also be represented by a minimum number of design variables to minimize the computational cost. In the present study, parametric modification function method (Kim et al, 2008) is adopted for the hull-form modification.

The initial hull surface is represented by using the following B-spline surfaces:

$$Q(u,v) = \sum_{i=1}^{n_i+1}\sum_{j=1}^{n_j+1} B_{i,j} N_{i,k}(u) M_{j,l}(v) \quad (11)$$

where the $B_{i,j}$ are the vertices of a polygon net, $N_{i,k}(u)$ and $M_{j,l}(v)$ are the B-spline basis function in the bi-parametric u and v directions, respectively.

The parametric modification function is superimposed on the original hull (H_{old}) to obtain modified geometry (H_{new}):

$$H_{new}(x,y,z) = H_{old}(x,y,z) + r(x)\cdot s(y)\cdot t(z) \quad (12)$$

The three parametric modification functions (*r, s* and *t*) are polynomial functions defined along the *x, y,* and *z* directions, respectively. The design variables for optimization can be changed using the functions and the modified geometry can be obtained using the perturbation with specific direction depends on design variables. In this paper,

1. Sectional area curve (SAC),
2. Section shape, and
3. Bulb shape

are used as design variables of the fore-body of the hull.

This parametric modification approach can also be applied to multiblock grids. The smoothness is guaranteed because the modified geometry is constructed by modification functions.

The main disadvantage of this approach is that it is not fully flexible and it allows us to obtain the modified geometry according to a given parametric modification function only. For more details of the present parametric modification function, see Kim et al (2008).

OBJECTIVE FUNCTIONS AND THEIR EVALUATIONS

Hydrodynamic design of ships involves several stages, from preliminary and early-stage design to late-stage and final design. It is clear that the preliminary and early hydrodynamic design requires 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 runs at the final stages of the design. Both potential-flow based simple CFD tools and Euler/RANS/Navier-Stokes based advanced CFD tools have been developed for the early-stage hydrodynamic design of displacement hulls and for the late-stage detailed flow analysis.

As the objective of this study is to demonstrate the effectiveness of the hydrodynamic optimization of hull forms using variable fidelity models, the objective function is simply defined as the wave resistance coefficient C_W. The optimal hull form is determined by minimizing the wave resistance coefficient C_W at a given speed ($F_N = 0.26$). The geometrical constraint is on the displacement (which is kept fixed ± 1% of the original value).

As the first step of testing variable fidelity models, the potential flow solvers with nonlinear and linear free surface boundary conditions are used as high-fidelity model and lower-fidelity model, respectively, to determine the optimal hull form by minimizing wave resistance coefficient of modern container ship for a given speed with displacement constraint.

High Fidelity Solver: Nonlinear Potential Flow Solver

The high-fidelity flow solver adopted for this test is based on the steady potential free surface flow theory with nonlinear free surface boundary conditions satisfied at the exact free surface position. The solution procedure used to solve Laplace equation subject to nonlinear free surface boundary conditions and other boundary conditions is based on the Rankine source panel method (Choi et al. 2001; Raven 1996). The wave-resistance coefficient C_W is evaluated by integrating the pressure over the wetted hull surface. The details of the nonlinear potential flow solver are given in Choi et al. (2001).

In this study, the hull surface and the free surface in the vicinity of the hull surface are divided into 1,848 and 2,250 quad panels, respectively, in the optimization runs. During the computation the ship was free to sink and trim according to pressure computed, through a simple fixed-point iterative procedure.

Lower-Fidelity Solver: Linear Potential Flow Solver

A practical design-oriented CFD tool, based on a new theory, called Neumann-Michell (NM) theory, is used as a lower-fidelity model to compute the steady flow about a ship. This theory is based on a consistent linear potential flow model (Yang, et al., 2007a;b). The NM linear potential flow model expresses the non-dimensional flow velocity at a flow-field point in terms of an alternative boundary-integral representation. The simplified free-surface Green function given in Yang et al. (2004) is used. The NM flow representation only involves distributions of singularities over the mean wetted ship hull surface. Thus, this linear potential flow model does not involve a line integral around the mean ship waterline, unlike the Neumann-Kelvin linear potential flow model. An iterative solution procedure is used to solve the alternate boundary integral representation. The first velocity used in this iterative scheme is the solution corresponding to the slender-ship approximation (Noblesse, 1983).

The details of the NM theory can be found in Yang et al. (2007a;b). The wave drag predicted by the NM theory is in fairly good agreement with experimental measurements. In addition, the computer code based on NM theory is very robust and highly efficient. Specifically, only surface meshes on the hull surface are required. The CPU time for evaluating the flow about a ship hull that is approximated by 10,000 triangular panels is approximately 10 seconds per Froude number using an Intel Pentium 4 Processor PC. In this study, the hull surface is divided into about 5,000 triangular panels in the optimization runs.

ILLUSTRATIVE APPLICATIONS

In order to demonstrate the effectiveness of the SQP based variable fidelity optimization, a container hull-form optimization problem is considered.

The optimizers are applied to the Kriso Container Ship (KCS) with ship length $L_{BP} = 230m$, ship beam $B = 32.2m$ and ship draft $D = 10.8m$. The optimal hull form is determined by minimizing the wave resistance coefficient C_W at a given speed ($F_N = 0.26$). The geometrical constraint is on the displacement (which is kept fixed ± 1% of the original value). The keel line is kept fixed, but bulb profile can be changed. The design variables are limited by some box constraints, which define the range to be explored as $40\% L_{BP}$, i.e., from Station 12 to the bulb tip. The optimal hull surface is joined smoothly to the original hull surface at Station 12.

Fore Hull Form Optimization Problem 1

The initial numerical experiments are conducted only for two design variables in order to visualize the algorithms' progress easily and completely. Fig. 2 shows the fore hull form of the KCS. Fig. 3 shows the comparison of original body plan and modified body plan due to the given change of the design variable that defines the section shape (left: DLWL type; right: U-V type), where DLWL type means the modification of the design load waterline, and U-V type means the modification of section shape.

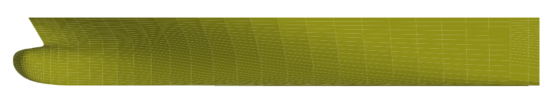

Fig. 2: Fore hull form of the original KCS.

In order to compare the conventional SQP method with variable fidelity method, the hydrodynamic optimization problem is first solved in a single-fidelity mode by using SQP method. Figs. 4a and 4b depict the level sets of the objective function and active constraints obtained by lower- and high-fidelity flow solvers, respectively. The shaded regions are infeasible design. The red dot is the value of the objective function corresponding to the initial design variables and the blue square is the value of the objective function corresponding to the optimal design variables obtained using lower- and high-fidelity flow solvers, respectively. There is an interesting finding between lower- and high-fidelity analyses. With high-fidelity analysis, the objective function increases when the value of the section shape-DLWL type increases. On the contrary, the objective function decreases when the value of the section shape-DLWL type increases with lower-fidelity analysis.

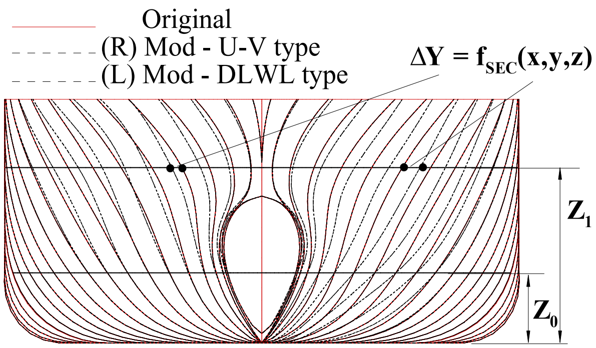

Fig. 3: Comparison of original body plan and modified body plan obtained by varying design variable (U-V type or DLWL type).

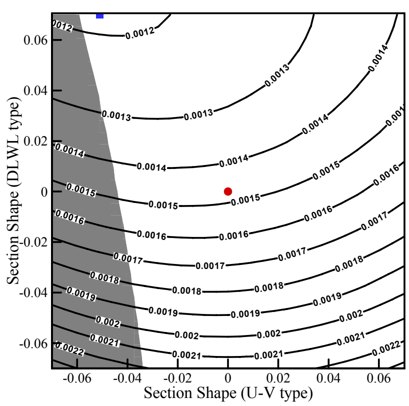

Fig. 4a: Level sets of the objective function and active constraints for optimization problem 1 obtained by lower-fidelity solver.

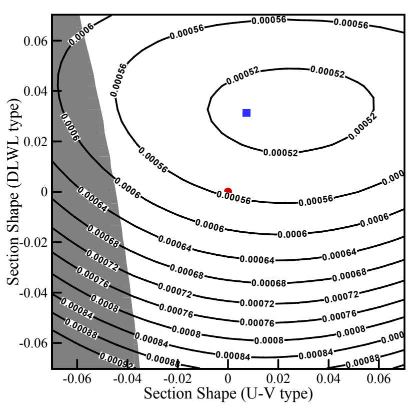

Fig. 4b: Level sets of the objective function and active constraints for optimization problem 1 obtained by high-fidelity flow solver.

Fig. 5 depicts the level sets of the objective function and active constraints obtained by variable fidelity optimization and conventional SQP method. In Fig. 5, the red dot is again the value of the objective function corresponding to the initial design variables; the green dot is the value of the optimal objective function obtained using variable fidelity models. In addition, the optimal objective function obtained using lower- and high-fidelity models are also plotted in Fig. 5 as magenta square and blue square, respectively. It can be seen from Fig. 5 that the result obtained from the variable fidelity optimization is convergent to the solution of the high-fidelity problem (Optimal 3 vs. Optimal 1).

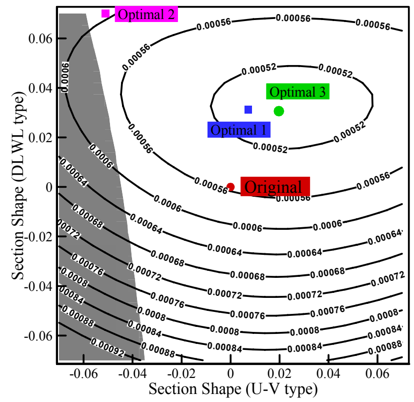

Fig. 5: Level sets of the objective function and active constraints for optimization problem 1 obtained by variable fidelity models.

The wave resistance coefficients, number of objective function evaluations and the optimal values of design variables obtained using lower-fidelity model, high-fidelity model and variable fidelity model are shown in Table 1. It can be seen from Table 1 that the objective function is evaluated 12 times by the high-fidelity model and 101 times by lower-fidelity model in the variable fidelity optimization. The objective function is evaluated 23 times by high-fidelity model in the high-fidelity optimization. The most time consuming part in the optimization is the evaluation of the objective function. The computational cost for the evaluation of the objective function using current lower-fidelity model is about 1% of that using high fidelity model. So the saving in the computational cost using the variable fidelity models is nearly 50% in comparison with that using the high-fidelity model alone.

Table 1: Numerical results of the fore hull form optimization problem 1, ΔF is the C_W reduction of the optimal hull form obtained in comparison to the original hull form

	Lower fidelity	**High fidelity**	**Variable fidelity**
Original $C_W \times 1000$	1.4692	0.55547	0.55547
Optimal $C_W \times 1000$ (ΔF)	1.1874 (19.2%)	0.51351 (7.6%)	0.50953 (8.3%)
Number of objective function evaluations	25	23	101 (L) 12 (H)
Design variable x1	-0.051	0.00728	0.0197
Design variable x2	0.070	0.0313	0.0306

Fore Hull Form Optimization Problem 2

Five design variables are now considered for the hydrodynamic optimization of the fore hull of the KCS. The wave resistance coefficients, number of objective function evaluations and the optimal values of design variables obtained using lower-fidelity model, high-fidelity model and variable fidelity models are shown in Table 2, where x0, x1, x2, x3, x4 denote five design variables.

It can be seen from Table 2 that the objective function is evaluated 20 times by high-fidelity model and 301 times by lower-fidelity model in the variable fidelity optimization. The objective function is evaluated 53 times by high-fidelity model in the high-fidelity optimization. So the saving in the computational cost using the variable fidelity model is more than 50% in comparison with that using the high-fidelity model alone.

Table 2: Numerical results of the fore hull form optimization problem 2, ΔF is the C_W reduction of the optimal hull form obtained in comparison to the original hull form.

		Lower fidelity	High fidelity	Variable fidelity
Original $C_W \times 1000$		1.4692	0.55547	0.55547
Optimal $C_W \times 1000$ (ΔF)		1.1680 (20.5%)	0.49910 (10.1%)	0.49512 (10.9%)
Number of objective function evaluations		54	53	311 (L) 20 (H)
x0	-0.5~0.5	-0.0087	0.0051	0.0139
x1	-0.07~0.07	-0.0431	0.1157	0.0259
x2	-0.07~0.07	0.0700	0.0288	0.0253
x3	-0.02~0.02	0.0200	0.0200	0.0200
x4	-0.02~0.02	0.0200	-0.0031	0.0140

Fig. 6 shows the comparison of the body plans between the original and the optimal hulls obtained using variable fidelity optimization and high fidelity optimization. The trend of the fore hull form modification is similar in both results.

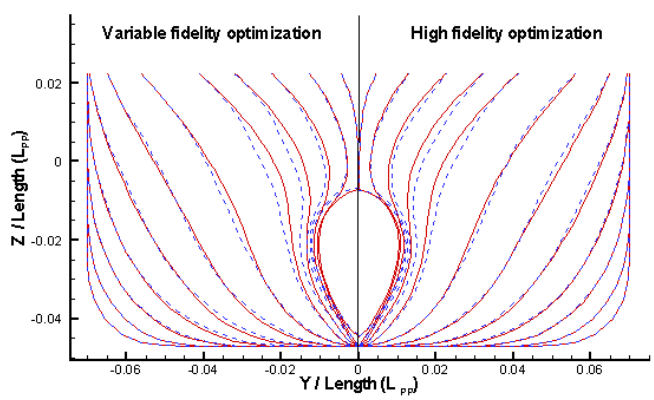

Fig. 6: Comparison of the body plans between the original and the optimal hulls obtained using variable fidelity optimization (left) and high fidelity optimization (right).

Fig. 7 and Fig. 8 depict the comparison of wave profiles and wave elevation contours obtained for the steady flow around the original hull form and the optimal hull form determined using variable fidelity model at $F_N = 0.26$. The experimental wave profile for the original hull (Kim et al., 2000) is also plotted in Fig. 7.

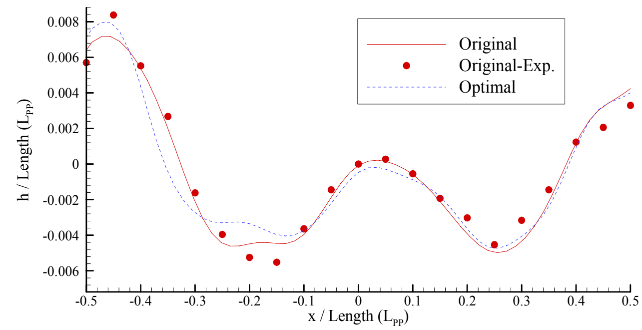

Fig. 7: Comparison of wave profiles obtained for the original hull form and optimal hull form using variable fidelity optimization.

It can be seen from Fig. 7 that the wave profile for the original hull form predicted by the high-fidelity flow solver shows fairly good agreement with experimental measurement. The distinct differences in wave profiles and wave elevations can be observed in Fig. 7 and Fig. 8, respectively, which is corresponding to the hull form change from the original hull form to the optimal hull form.

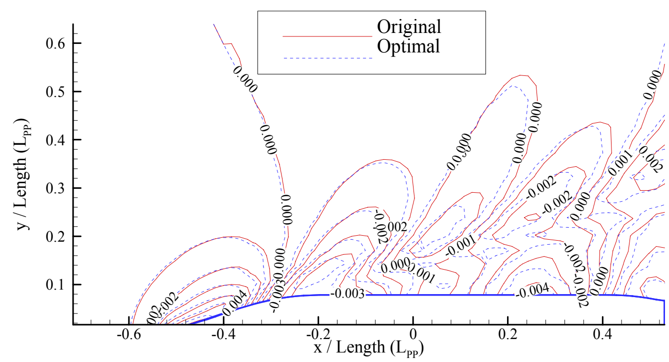

Fig. 8: Comparison of wave elevation contours obtained for the original hull form and optimal hull form using variable fidelity optimization.

Fig. 9 shows the comparison of wave resistance coefficient for the original hull form and optimal hull form obtained using variable fidelity models. The residual resistance coefficient (Kim et al., 2000) is also plotted in Fig. 9. It can be seen from Fig. 9 that the results obtained using the high-fidelity flow solver shows fairly good agreement with experimental measurement for the original hull form. It can also be observed that the wave drag coefficient of the optimal hull form obtained using variable fidelity models at $F_N = 0.26$ is lower than that of the original hull form in all Froude numbers.

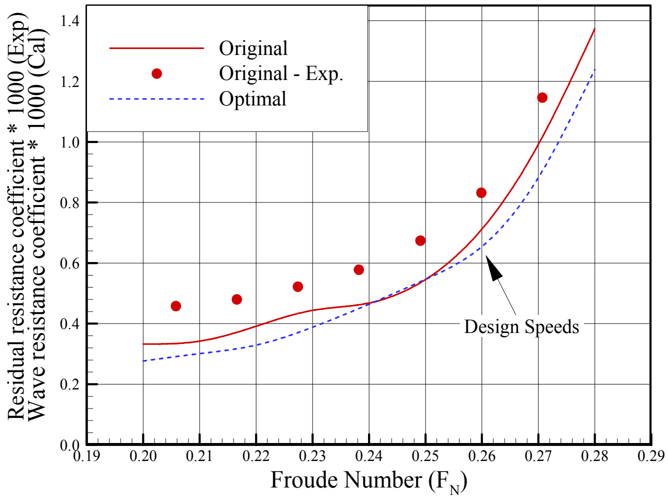

Fig. 9: Comparison of wave resistance coefficient obtained for the original hull form and optimal hull form using variable fidelity optimization.

CONCLUSIONS

A practical hydrodynamic optimization tool has been developed for the design of monohull ships. This tool adopts the variable fidelity method that uses lower-fidelity models and a scaling function to approximate the higher-fidelity models to reduce computational cost. For purposes of illustration, the potential flow solvers with nonlinear and linear free surface boundary conditions are used as high-fidelity model and lower-fidelity model, respectively, in the present hydrodynamic optimization tool to determine the optimal hull form of a modern container ship by minimizing the wave resistance for a given design speed with displacement constraint.

Numerical results show that the present hydrodynamic optimization tool can maximize the use of lower-fidelity, cheaper models in iterative procedures. It can also be observed from the illustrative examples that the variable optimization can produce the similar optimal hull form as the high-fidelity optimization but with considerable saving in the computational cost because the current lower-fidelity CFD tool used to evaluate the objective function is a highly efficient tool. Numerical results have also demonstrated that the current hull surface representation and modification methods are effective in generating new hull forms. The wave resistance reduction in entire speed range has been achieved using present variable fidelity hydrodynamic optimization tool.

The present wok is the first step of the development of a practical hydrodynamic optimization tool using variable fidelity models. An Euler/RANS based finite-element flow solver has been adopted as a high-fidelity model to replace the nonlinear potential flow solver in the ongoing research. The preliminary results have demonstrated that the present variable fidelity optimization tool works very well with different high-fidelity models.

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