An Automated Methodology for Multi-objective Optimization of Hull Forms

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Abstract

The traditional ship design process is often under the control of geometric modeling of the boat form. After this, model performance is analyzed with various simulations. If the result is not satisfactory, the iterative steps are repeated until the desired performance is obtained. These hull forms, which revealed by these method, are usually a negotiated solution rather than the optimum, that partially reflects the different performance criteria.
In this paper, an automated hull form optimization methodology is developed based Simulation Driven Design method with using new generation of design, analysis and optimization software combination. For this purpose, parametric modeling software called FRIENDSHIP-Framework is used to collect the optimization process under one roof and handle the process automatically. Aforementioned methodology is used to develop a systematical hull form series for frigate-type surface warships. Next stage, an alternative design chosen as sample and a multi-objective optimization process is performed. After optimization, initial and optimum hull forms are compared to show that how to improve the resistance and seakeeping results with some local changes.

Key words: Parametric modeling, multi-objective optimization, computational fluid dynamics

1. Introduction

In recent years, form optimization studies based on computer simulations has become a deciding factor in the design of more efficient and environmentally friendly ships. Optimization of the hydrodynamic properties of the hull form plays an important role at the preliminary design stage. With the development of computer technology, researchers have worked on to integrate modeling and simulation methods with each other. Despite this integration become successful in the field of structural mechanics, it could not be fully realized in the field of fluid dynamics because of quite a lot dependency of fluid dynamics to geometric model.

Form optimization studies in ship design began in the middle of last century. First optimization studies were realized with analytical connections between hull form geometry and wave resistance. This studies were focused on the methods based on Michell's integral, like thin ship theory. Since the beginning of the eighties, form optimization studies has started to shift towards the use of the computational fluid dynamics (CFD) methods.

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CFD covers a wide area in ship hydrodynamics includes viscous and non-viscous methods. Non-viscous methods are often used in the solution of the wave resistance problems including nonlinear free surface boundary conditions. Viscous methods, in case, are based on the solution of Reynolds Averaged Navier Stokes RANS equations that include effect of turbulence. In the literature, potential flow methods are mostly preferred in global form optimization and systematic variation works. The main reason is that these techniques can respond much faster for the analysis of a wide range of alternative hull forms. Furthermore, they are suitable for automatic optimization process. Viscous effects were mostly considered in local optimization works like optimization of appendages. Another disadvantage of RANS methods is that creating the mesh structure is difficult, time-consuming and hard to be adapted to an automated variation process.

In the early nineties, studies realized by Janson, Larsson et al. [1], [2], [3], [4] are the first samples that all resistance components was calculated by CFD methods and an optimization approach was used. Researchers have integrated their CFD-code, called SHIPFLOW, with an optimization module and surface modification software. A number of points on the hull surface was selected as free variables and systematically moved at the constant displacement. Harries and Abt [5] have introduced a new approach to the optimization of ship form with CFD methods in the study published in 1999. Researchers studied the process as two separate optimization problems, internal and external optimization. Internal optimization problem is modeling the hull geometry with several form parameters according to fairness criteria. External optimization problem is to derive the hull form systematically with the change of selected parameters and improve the hydrodynamic properties of the hull form. In the study, optimization of a high speed vessel hull form was performed due to the integration of the geometric modeling software FRIENDSHIP, based on parametric modeling, and SHIPFLOW.

In this paper, an automated hull form optimization methodology is developed based Simulation Driven Design method with using new generation of design, analysis and optimization software combination. For this purpose, parametric modeling software called FRIENDSHIP-Framework is used to collect the optimization process under one roof and handle the process automatically. The whole process can be divided to 4 main stages: preliminary design, parametric modeling, systematic variation and multi-objective optimization. Aforementioned methodology is used to develop a systematical hull form series for frigate-type surface warships. Next stage, two hull form are chosen as sample and a multi-objective optimization process is performed. After optimization, initial and optimum hull forms are compared to show that how to improve the resistance and seakeeping results with some local changes.

2. Methodology

The automated multi-objective hull form optimization methodology can be examined under 4 main stages: preliminary design, parametric modeling, systematic variation and multi-objective optimization. The essential objective of the first stage is to specify the design space and the constraints, like dimensional, stability and seakeeping constraints. To specify the design space and the constraints, the type and the mission features of the vessel should be decided. A preliminary superstructure design should be beneficial to define the significant locations for stability and seakeeping analyses. In this paper, a frigate-type surface warship was selected to perform the optimization methodology. The whole process is fully automated and be controlled by FRIENDSHIP-Framework. Main objective is to optimize the parent form with regards to resistance. Therefore, the parent hull form was designed as full-parametric and a number of alternative hull forms were produced by systematic variation methods. During the variation stage, calm water resistance analyses, seakeeping analyzes and a small stability control were carried out for each alternatives to eliminate unfeasible designs. Then a multi-objective optimization was performed to selected variants with some local variables.

2.1. Parametric modeling

In order to handle the global optimization process the hull form geometry is needed to modify. This process takes extremely important place in the optimization loop. Because form variation consist of not only changing the parameters such main dimensions, but also requires to provide some constraints like constant displacement, surface smoothness, etc.

Harries [6] has brought a new approach to geometric modeling of the hull form. This approach is based on modeling the curves and surfaces that create the hull geometry depending on several form parameters. In this method, form parameters could be main dimensions or some hydrostatic values, like displacement, c_b, etc. even different types such as coordinate, angle, etc. Geometric forms are represented by curves and surfaces modeled based on these parameters, so alternative forms can be produced by changing the parameters systematically. As a result of ongoing research, the parametric modeling software called FRIENDSHIP-Framework has emerged. The main innovation of the software is the use of a new kind curve, called the F-spline. F-spline is an optimized curve for smoothness and can be defined with a beginning and an ending point and their tangent angles. Harries and Abt [7] has reported that, F-spline curve has been revealed as a result of optimization for Fairness Criteria (Eq. 2) of a B-spline curve consist of *m* points and the degree of *k*, expressed as in Eq. 1;

$$Q(t) = \begin{pmatrix} x(t) \\ y(t) \end{pmatrix} = \sum_{i=0}^{m-1} V_i . N_{ik}(t) \tag{1}$$

$$E_n = \int_{t_B}^{t_E} \left(\left(\frac{d^m x}{dt^n} \right)^2 + \left(\frac{d^m y}{dt^n} \right)^2 \right) dt, \quad n = 1,2,3$$
(2)

In this paper, the flowchart shown in Fig. 1 was used to model the parametric form. Several form parameters and design variables have been identified to use in modeling and variation. Also some function codes have been written to modify or apply some modeling and control operations as required.

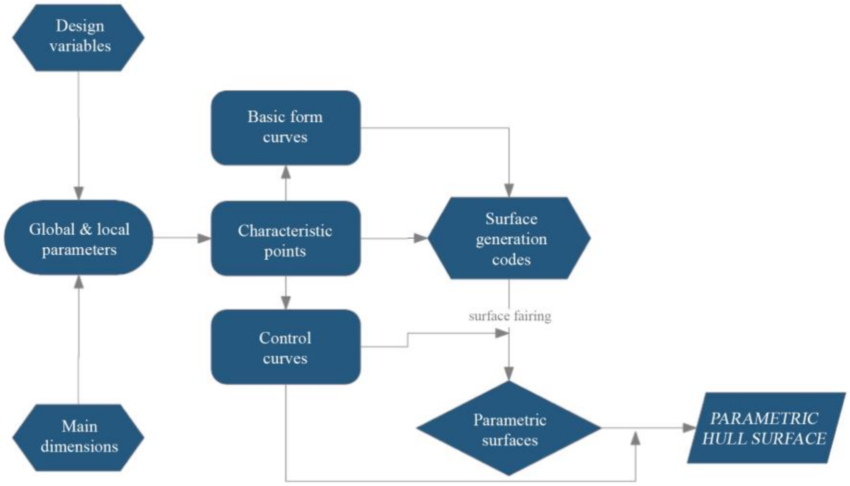


Figure 1. Stages of parametric hull form modeling

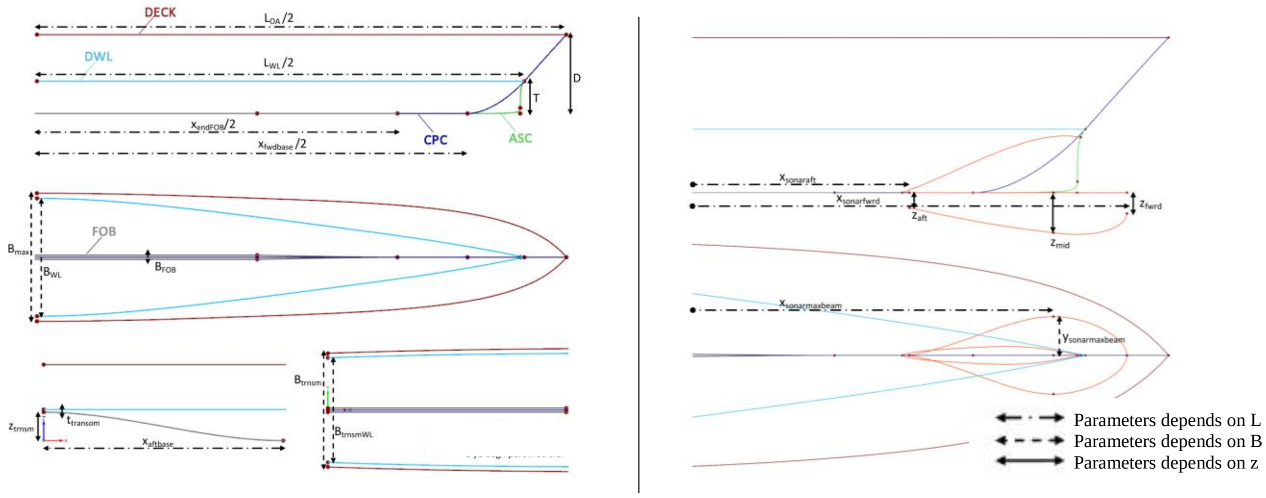
The main dimensions and some non-dimensional coefficients of the fully-parametric parent hull form was given in Table 1.

Table 1. Main dimensions of the parent hull form

Length overall, L_{OA} (m)	145	L_{WL} / B_{WL}	8.3
Length waterline, L_{WL} (m)	139	L_{WL} / $\nabla^{1/3}$	7.75
Maximum breadth, B_{max} (m)	18.203	LCB/L_{WL}	0.44
Waterline breadth, B_{WL} (m)	16.747 (B_{max}*0.92)		
Depth, D (m)	11.2		

To model the hull form fully-parametric it was needed longitudinal basic curves to define the outline of the geometry, as shown in Fig. 2a. Additional adaptive curve was created to be able to optimize the bow form. This curve was modeled subject to various parameters to allow the formation of different bow types. Similarly some additional parametric curves were created to add a sonar dome to the bow, as shown in Fig. 2b.

Hull surface was modeled by means of parametric form curves as meta-surface, which is a new parametric and optimized surface type in Friendship-Framework controlled by parametric control curves [8]. Final surface of the parent hull is given in Fig. 3. The hull surface is completely controlled by parameters and new forms to be created with the change of parameters will have a smooth surface, such as the parent hull form. Thus, hull form has prepared for systematic variation and optimization stages.



(a) (b)

Figure 2. Curves used in parametric model (a) Basic curves (b) Curves for sonar dome

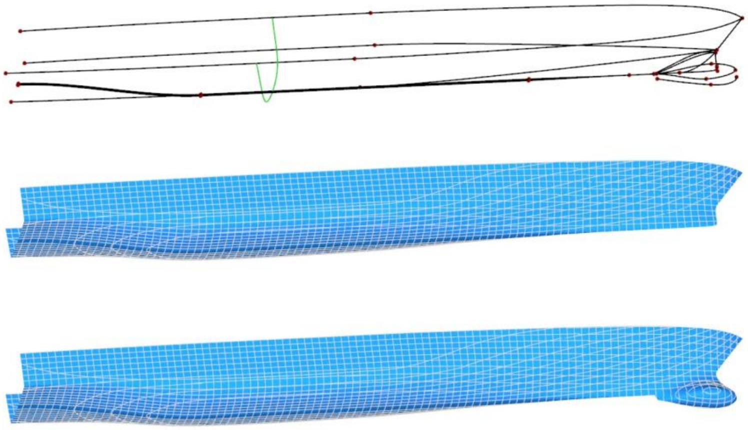


Figure 3. Parametric surface of parent hull forms

2.2. Systematic variation and hydrodynamic performance analyses

The parameters have been divided to two different sets. “Global parameters” including main dimensions were changed systematically to create alternative hull forms. Also it was decided to keep some parameters constant. Selected variable and constant parameters and the bounds for the variables are shown in Table 2.

Whole process is operated automatically under the control of FRIENDSHIP-Framework. Each alternative hull form was created according to alteration of design variables and hydrostatic values were calculated. The modified surface of the alternative hull was sent to SHIPFLOW and Maxsurf/Seakeeper software to resistance and seakeeping analyses, respectively. The results of analyses were also compiled in FRIENDSHIP-Framework.

Table 2. Variable and constant parameters used in systematic variation

Variable parameters			
$\mathbf{L_{WL}/B_{WL}}$	7.5, 7.7, 7.9, 8.1, 8.3, 8.5, 8.7, 8.9, 9.1		
Ⓜ$\mathbf{=L_{WL}\ /\ \nabla^{1/3}}$	7.5, 7.75, 8, 8.25, 8.5		
$\mathbf{LCB/L_{WL}}$	0.42, 0.44, 0.46, 0.48, 0.50		
Constant parameters			
$\mathbf{L_{WL}}$	139 m	$\mathbf{C_B}$	0.490
$\mathbf{L_{WL}/D}$	12.4	$\mathbf{C_P}$	0.607
$\mathbf{i_E}$	12^o	$\mathbf{C_{WPaft}}$, $\mathbf{C_{WPfore}}$	0.984 , 0.600
$\mathbf{B_{max}/B_{WL}}$	0.92	$\mathbf{C_M}$	0.807
$\mathbf{B_T/B_X}$	0.92	$\mathbf{t_{transom}}$	0.4 m

Waterline length and depth was kept constant for all alternative hulls, so the center of gravity was assumed not changed. Draught value was altered to fix the displacement value in 5 groups created by altering the Ⓜ value.

2.2.1. Resistance analyses

Because of the high number of alternative designs, CFD analyses were performed according to potential theories with SHIPFLOW for two Froude number, Fn = 0.251 and Fn = 0.418. Wave resistance values were obtained from XPAN module, and frictional resistance values were calculated according to ITTC and alternatively obtained from XBOUND module that use boundary layer method. For form factor k=0.15, total resistance for each alternative design were calculated according to Eq. 3;

$$R_t = R_w + (1+k)R_f \tag{3}$$

2.2.2. Seakeeping analyses

Seakeeping analyses were performed for two Froude number, Fn = 0.251 and Fn = 0.418, 5 sea state condition and waves from 5 different angles (0^o, 45^o, 90^o, 135^o, 180^o). For each alternative design, characteristic pitch angle and vertical accelerations were calculated at specified locations (Fig. 4) for the given conditions. The values used in seakeeping calculations are given in Table 3.

Table 3. The values used in seakeeping calculations

Characteristic wave height (m)	3.25
Modal period (s)	10.16
Wave spectrum	2-parameter Bretschneider
VCG (m)	8

2.2.3. Constraints

To be able to evaluate the alternative hull forms and eliminate unfeasible designs, various seakeeping and stability rules was taken as constraints, as shown in Table 4.

Table 4. Constraints used in variation and optimization process

Constraint	Value	Location	
Vertical acceleration (RMS)	0.2g	Bridge	STANAG 4154 [9]
Characteristic pitch angle (^{o})	1.5	-	STANAG 4154 [9]
Min GM (m)	0.3	-	Royal Navy [10]

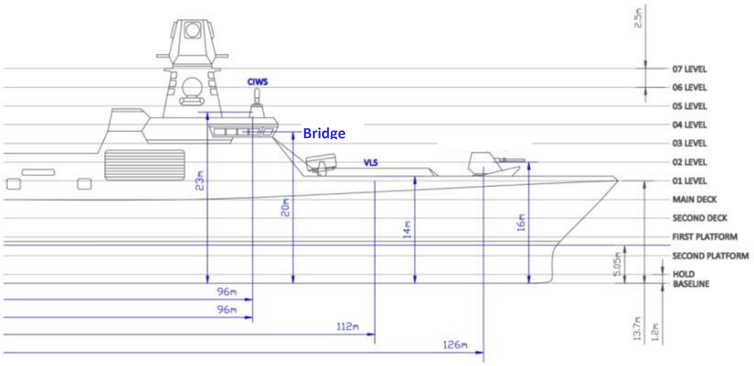


Figure 4. Specified locations and coordinates for seakeeping analyses

At the end of systematical variation, 225 alternative hull forms were created divided into 5 different displacement group and additionally 225 hull forms with sonar dome.

2.3. Multi-objective optimization

In this paper, it is intended to perform an automated multi-objective optimization process. As a result of the literature review regarding multi-objective optimization it is preferred to use NSGAII algorithm because of rapid and better convergence [11].

In systematic variation it was used "global parameters" related with main dimensions. In optimization stage, in case, global parameters were kept constant and new "local variables" were defined. This variables were connected with stern and bow form, so it was provided to optimize parent hull form on the basis of both main dimensions and regional. It was also defined three more variables for sonar dome. All variables used in optimization and their upper and lower bounds are given in Table 5.

Table 5. Design variables used in optimization stage

	Parameter	Definition	Lower bound	Upper bound
Stern form	B_{tr} / B_{WL}	The ratio of transom breadth to breadth at waterline	0.75	0.95
	sternTan (^{o})	The angle of connection of profile curve and transom	87	93
Bow form	i_E (^{o})	Entrance angle	6	16
	stemShift (% L_{WL})	Variation of underwater part of stem form	-2.73	1.44
	dxMaxSec (% L_{WL})	Displacement of frame with maximum sectional area	-2.16	2.16
Sonar dome	$X_{sonarmaxbeam}$ (% L_{WL})	Longitudinal disp. of maximum breadth of sonar dome	-0.7	1
	$Y_{sonarmaxbeam}$ (% B_{WL})	Displacement of maximum breadth of sonar dome	-1.8	1.8
	$X_{sonarfwrd}$ (% L_{WL})	Longitudinal displacement of sonar dome tip	-1.4	0.7

In this paper, a design coded YFS-069 was picked as a sample for optimization process from the Ⓜ=7.75 group. This was a hull form which have minimum value of equally weighted average of total resistance values obtained for two Fn values. The global parameters was kept constant and local improvements was carried out with new local variables.

To perform a multi-objective optimization, three objective function was selected;

- Minimize $R_{T,\ Fn=0.251}$ (resistance objective)
- Minimize $R_{T,\ Fn=0.418}$ (resistance objective)
- Minimize $Vacc_{bridge}$ (seakeeping objective)

3. Results and discussion

At the end of optimization process, 335 alternative design were created from YFS-069 with alteration of local variables. If the results were analyzed on the basis of single objective, following optimum designs could be obtained for different objective functions;

- min R_T @ Fn=0.251 des025
- min R_T @ Fn=0.418 des067
- min V_{acc} des159

Vertical acceleration and resistance values at two different speeds are given in three-dimensional graphic in Fig. 5. Highlighted designs are the optimum vessels obtained as a result of pairwise comparisons. The graphs of the pairwise comparisons are given in Fig. 6.

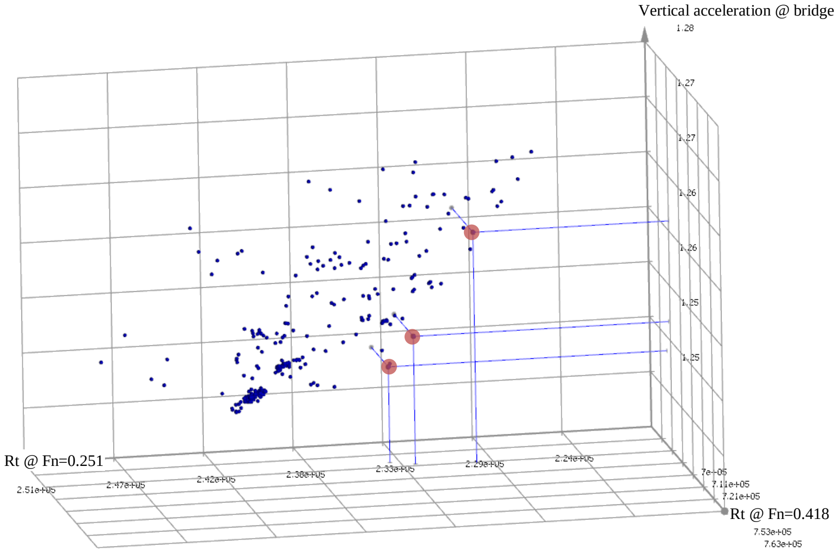


Figure 5. Results of all designs for three objective functions

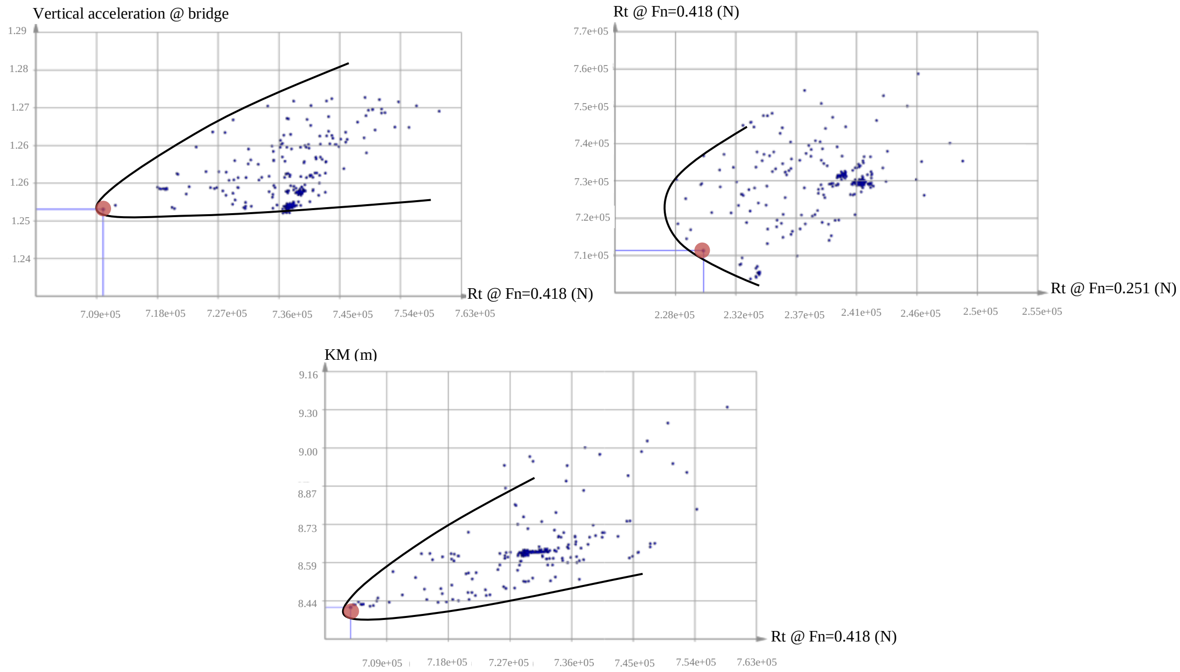


Figure 6. Pairwise comparison graphs of all designs with Pareto curves

Wave height contours of initial design and optimal design for resistance are shown in Fig. 7 comparatively. The lower half of the figure represents the optimum design and the upper half the initial design. As can be seen from the figure, optimized design have more uniform wave distribution and lower wave height.

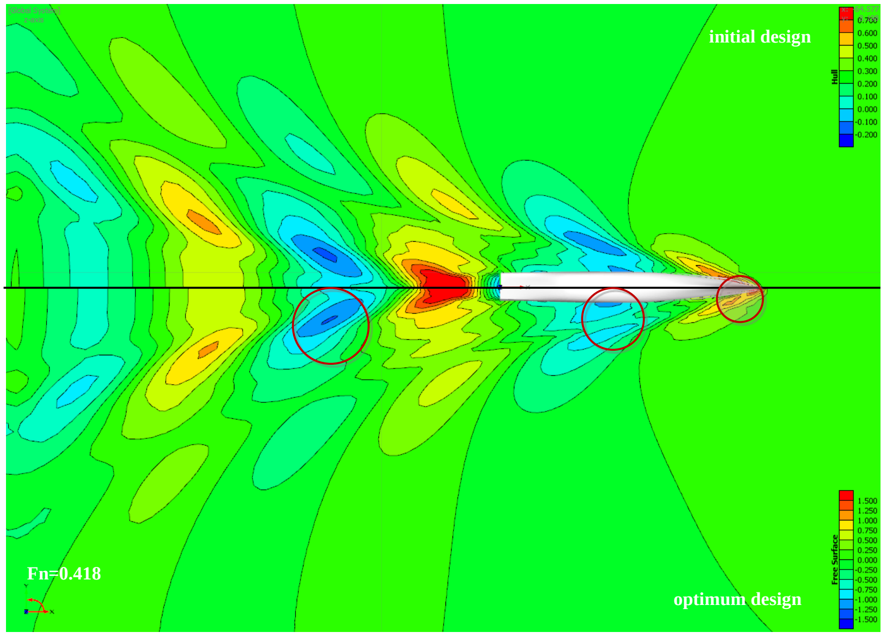


Figure 7. Comparison of initial and optimal design (Upper: initial design, Lower: optimal design)

As can be seen from the figure, optimized design have more uniform wave distribution and lower wave height. As a result of multi-objective optimization it can be obtained different optimal designs according to different objectives. Hence, the optimal design should be selected by the designer with deciding the objective which is more dominant.

Results are important with regards to determine the design space and predict the vessel performance at preliminary design phase and give the designer an opportunity to compare the alternative geometries. To find the real resistance value of a design a more detailed CFD analyze includes viscous effects should be performed.

Conclusions

In this paper it is targeted to introduce an automated variation and multi-objective optimization methodology. The stages of whole process was presented and applied to a generic fully-parametric modeled surface combatant. Results show that the optimization methodology could be used to create systematic series and make global and local optimizations.

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