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Application of multi objective genetic algorithm in ship hull optimization

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Abstract. Ship hull optimization is categorized as a bound, multi variable, multi objective problem with nonlinear constraints. In such analysis, where the objective function representing the performance of the ship generally requires computationally involved hydrodynamic interaction evaluation methods, the objective functions are not smooth. Hence, the evolutionary techniques to attain the optimum hull forms is considered as the most practical strategy. In this study, a parametric ship hull form represented by B-Spline curves is optimized for multiple performance criteria using Genetic Algorithm. The methodology applied to automate the hull form generation, selection of optimization solvers and hydrodynamic parameter calculation for objective function and constraint definition are discussed here.

Keywords: multi objective genetic algorithm; ship hull optimization; seakeeping; nonlinear programming; EEDI

1. Introduction

Prediction of design variables that results in a desired performance enhancement is of interest in all engineering fields. The benefits of design optimization are significant and hence can be found in many disciplines including aerospace, mechanical, material science and in marine. For example, a small improvement in the fuel efficiency of a ship may result in savings on the order of millions of dollars per year. The fuel efficiency is also important for reduction in greenhouse gas emission, which is a major component in the evaluation of International Maritime Organization (IMO)'s Energy Efficiency Design Index (EEDI).

A number of alternatives are being evaluated to increase the energy efficiency of the ship with careful consideration of safety of the vessel in sea. A staggering 9% savings has been recorded by the largest ocean cargo line Maersk in the first quarter of 2010 by reducing the ship speed (White 2010). This encouraged new ship developers to reduce the installed power on the ships to increase the fuel efficiency. It is, however, essential to ensure enough propulsive power is available to maneuver through adverse environmental conditions. Therefore, the optimization of hull form with speed consideration should not only reduce the steady resistance of the hull, but also ensure

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seakeeping performance and maneuverability in the rough sea conditions. Other alternatives include refinement of the complete hull form for new ships or just replacing the bulbous bow with a more suitable one for the modified operational condition of existing hull forms. Finding the optimum route based on metocean data or enhancing the capability of autopilots to utilize real time local sea condition to select best ways to maneuver the ship are some of the other methods that are also being evaluated.

The hull form optimization in the context of naval architecture poses three main challenges: Parametric representation of the ship hull relevant in design perspective, accurate estimation of hydrodynamic interaction forces and resulting motion of the ship, and finally, the optimization routine that relies on definition of desired performance objectives and searches for the global minima associated with the combination of design variables. To solve the ship hull optimization problem described above, it requires understanding of three major research disciplines: Computer Aided Design, Computational Hydrodynamics and Global Optimization. A brief discussion on each of these topics and final selection of a suitable method applied for the ship hull optimization will be presented here.

2. Parametric hull suitable for optimization

A number of factors influences how the ship hull needs to be parameterized. The most general case that one can imagine may be a semi-solid shape free to distort in any direction conforming to a definitive shape that is ideal for all performance objectives and constraints. Defining all the constraints related to manufacturing capability, operating conditions, and aesthetics and comfort sought by human in a useful mathematical form is yet to be achieved. Therefore, most researchers adapt to a rather practical approach to define ship hull in terms of well-established naval architects definition and perturb the design variables ensuring most fundamental requirements of the ship will be satisfied naturally. Smith *et al.* (1990) shows one such example where the hull form is defined using Lewis forms that rely on principal particulars such as length, breadth, draft, prismatic coefficient, center of floatation etc. A similar approach is found in Kükner and Sariöz, (1995). Harries and Valdenazzi (2001) represented the hull form of a Ro-Ro ferry completely in terms of parametric curves and use it in optimization. This method is later followed by Maisonneuve *et al.* (2003), Birk and Clauss (2008), Kim (2009) to name a few. Perhaps, the closest to our imagined semi-solid hull form, is experimented by Heimann (2005), where the ship hull is represented directly in terms of panels and the panels were moved based on optimized source strengths values. The variation in panel position allowed here, however, was very small to keep a practical hull shape. Another approach that comes instinctively to any naval architect is to represent the ship hull in terms of offset points. Sariöz (2009) shows application of one such method in optimization where the offset points were used as optimization variables. Even though, this approach is ideal to apply on an existing hull form, having such large number of optimization variable is still not suitable for optimization purposes. Hence, only a limited portion of the hull form was optimized with limited freedom for the offset points to avoid impractical shapes.

Among all these methods, representing the ship hull using parametric curves controlled by limited number of well understood hull parameters was found to be most appropriate. Hence, for this study, an automatic ship hull generation script has been developed following the work of Petersen *et al.* (2009), which uses twenty five hull parameters (see Table 1) to generate section curves and then the ship hull surface in a common CAD format as shown in Fig. 1.

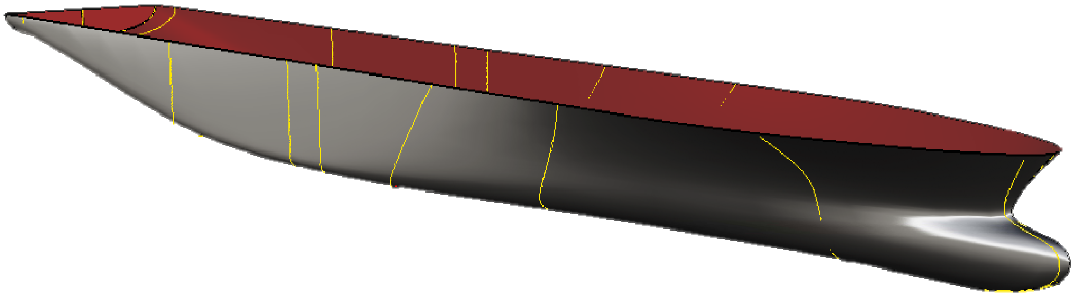


Fig. 1 Parametric ship hull

Table 1 Parameters used to define the ship hull

Si #	Parameters	Sample values	Si #	Parameters	Sample values
1	Length	242	14	BulbLowerAngle	0.0
2	Beam	32.2	15	BulbUpperAngle	47
3	Draft	10.8	16	BulbUpperLength	7.0
4	PropellerClearance	11	17	SternI	0
5	BilgeRadius	3.0	18	SternII	4.0
6	Height	17	19	ParallelMidshipI	32.6
7	DeadRiseAngle	3	20	ParallelMidshipII	51
8	FlatOfSideAngle1	52	21	ParallelMidshipIII	55.2
9	FlatOfSideAngle2	60	22	FlatOfSideI	63.4
10	BulbWidth	4	23	FlatOfSideII	78.6
11	BulbLength	12	24	FwdShoulder	101.1
12	BulbHeight	8	25	BowContour	111
13	BowOverHangAngle	47			

3. Estimation of hydrodynamic interaction forces and vessel motion

The primary concern in ship hull optimization is to reduce the fuel consumption (and consequently reduce CO_2 emission) without significant loss of travel time and any compromise in the stability requirements. The hydrodynamic criteria to achieve these goals are generally obtained by solving the fluid structure interaction problem numerically. For ship wave interaction potential theory based methods serve the purpose of initial evaluation of a large number of design variables as they are significantly more time efficient compared to nonlinear viscous fluid analysis using

Reynolds Average Navier Stokes Equation (RANSE) solvers. Also, the viscous effects are primarily dominant in the aft region of the vessel (Grigoropoulos and Chalkias 2010), and can be analyzed using experimental or numerical codes with viscous flow analysis capabilities after initial selection of suitable hull form through potential flow methods. In terms of performance criteria, the steady resistance in calm water is generally considered. It is however possible to incorporate criteria for superior seakeeping qualities, as will be demonstrated in this study, from the preliminary design optimization stage.

The hydrodynamic loads on a ship travelling with steady forward speed is solved using a frequency domain 3D Green function based panel method code named MDLHydroD. The theoretical background, numerical implementation and validation details can be found in Guha (2012), Guha and Falzarano (2013) and Guha and Falzarano (2015a). Second order forces and moments also have significant effect on ship propulsion, most importantly the longitudinal component known as the added resistance. A near-field pressure integration approach is applied to obtain the added resistance, which requires discretization of underwater hull surface only, which is ideal for hull optimization. Guha and Falzarano (2015b)and Somayajula *et al.* (2014) provides the complete details on analysis method and validations of added resistance. An interface to automatically prepare the panelization of the hull form and other environmental input parameters is developed. The automated panelization method was able to successfully calculate a smooth RAO curve around the resonance frequency for the vertical motions, which is essential for defining the seakeeping criteria used in this study.

4. Ship hull optimization procedure

4.1 The optimization problem

Any design optimization problem may be mathematically formulated as minimization of an objective function $f\left(\boldsymbol{x},\boldsymbol{p}\right)$, with free variable vector $\boldsymbol{x}=\left(x_1,x_2,\ldots,x_N\right)^T$ representing parameters allowed to vary during optimization and fixed variable vector $\boldsymbol{p}=\left(p_1,p_2,\ldots,p_M\right)^T$, which are not altered but may be required to calculate the objective function. Afterwards, in most practical problems, the optimization procedure has to solve the constrained minimization problem(Clauss and Birk 1996)

$$\begin{aligned}&\text{Find the vector } \boldsymbol{x}=\left(x_1,x_2,\ldots,x_N\right)^T\\&\text{which satisfies the equation}\\&f\left(\boldsymbol{x},\boldsymbol{p}\right)=\min\left[f\left(\boldsymbol{x},\boldsymbol{p}\right)\right],\\&\text{and the constraints}\\&g_j\left(\boldsymbol{x},\boldsymbol{p}\right)\geq 0\left(j=1,2,\ldots,l\right)\end{aligned}\tag{1}$$

The ship hull optimization problem may be categorized as bounded, multi variable, multi objective problem with nonlinear constraints. The objective function used in such optimization studies generally cannot be represented explicitly in terms of the variables $\left(\boldsymbol{x},\boldsymbol{p}\right)$, but are represented as a combination of selected response variables obtained by performing numerical simulations. As a result, the minimization problem solver has to search for the global minima surrounded by many local minimums. As most nonlinear programming algorithms are capable of solving a unimodal problem, in other words, a function with only one minima, it requires application of unconventional methods, sometimes with no theoretical certainty of achieving the global minima. A number of such optimization solvers are evaluated to determine the most appropriate solver for hull optimization problem.

4.2 Selection of optimization solver and objective function

Considering the complexity of the hull optimization problem, an analytical function known as the *Shubert Function* with multiple local minima and multiple global minima (see Fig. 2) is chosen to determine which optimization solver is best suited to solve the problem. An initial selection of optimization solvers are made from a number of available solver in the MATLAB® Global Optimization Toolbox (GOT), which are

- Sequential Quadratic Programming (SQP)
- Pattern Search (PS)
- Interior-Point (IP)
- Simulated Annealing (SA)
- Particle Swarm Optimization (PSO)
- Genetic Algorithm (GA)

The test results are shown in Fig. 3 where the minima and maxima of the objective function is shown as filled contour plots and the design variable values used in each iteration is shown as red circles. Except the Genetic Algorithm, all other requires an initial guess which is shown as a star marker in the figure. The first three optimization solvers (SQP, PS and IP) are found to be very sensitive to the initial guess and prone to get stuck in a local minima. The configuration options are also limited, which results in not being able to find the global minima unless a very good initial guess is made. The other three (SA, PSO and GA) were considerably more robust and were able to determine the global minima in most of the trials. Caution must be taken in setting up the configuration properties of these solvers as well, which otherwise may result in determining a local minima.

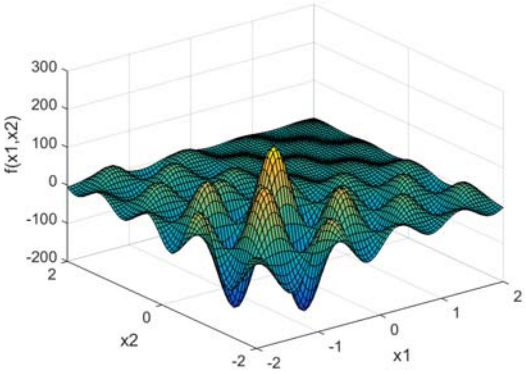
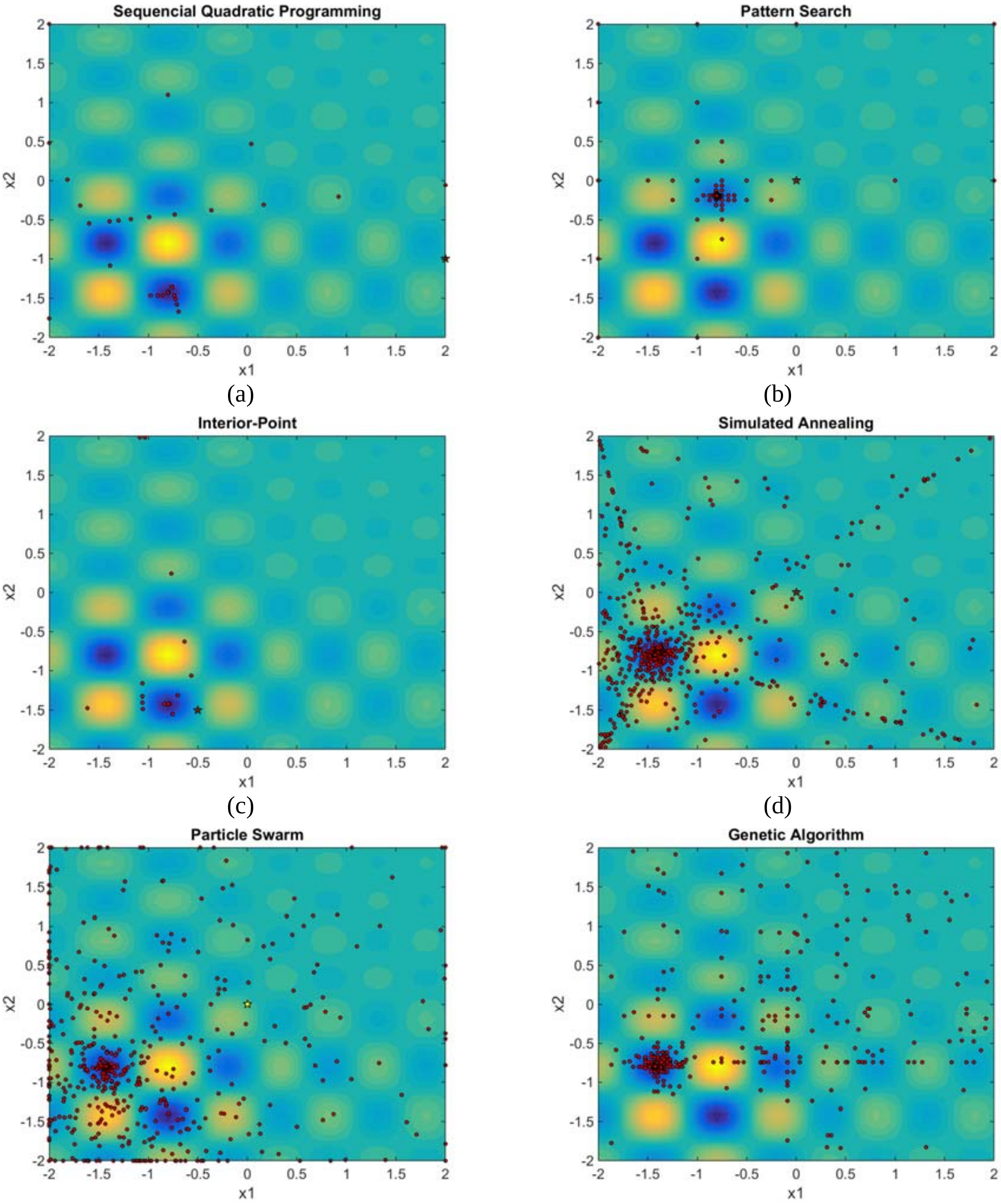


Fig. 2 Shubert function



(a) (b)

(c) (d)

(e) (f)

Fig. 3 Comparison of optimization solvers

The literature reviewed during this study suggest that there is no standard rule set for determining the seakeeping or propulsive performance of a ship which would ensure optimum performance in all conditions. Kükner and Sariöz (1995) combines the rms heave, rms pitch and probability of slamming events together to define their objective function and uses nonlinear direct search techniques for the optimization. Harries and Valdenazzi (2001) optimizes a Ro-Ro ferry in terms of calm water resistance (calculated using WARP), added resistance and an undefined Motion Sickness Index (MSI) calculated from seakeeping response obtained using a strip theory based code SOAP. A similar attempt is made by Biliotti *et al.* (2011) to optimize a patrol vessel considering its two main operational condition, normal patrol at 20knot and maximum speed of 35knots, based on empirical expression containing variance of wave profile along the water line, wave resistance, displacement and an undefined seakeeping operability index. Campana *et al.* (2006) uses minimization of wave resistance as objective while set a fixed upper limit as an inequality constraint for the heave and pitch responses. Tahara *et al.* (2011) uses a multi objective optimization where the wave resistance and a combination of acceleration and velocity at the bridge deck is minimized. Recently, Bagheri *et al.* (2014) shows optimization of classical Series 60 and Wigley hull based on acceleration at the bow of the vessel in regular head waves, while Kostas *et al.* (2015) uses a T-spline based geometry for resistance optimization.

Similar treatment of the objective function is found for offshore platforms as well. Peltzer *et al.* (1995) uses a Particle Swarm Optimization method to optimize a novel platform design based on weighted average of motions at different locations. Birk and Clauss (2008) minimizes the significant amplitude of cyclic tendon force obtained in random sea created using Pierson-Moskowitz spectrum.

A number of RANSE based optimization has also been performed by many researchers. However, due to the significantly large simulation time taken by each hull, it is prudent to fist reduce the number of test cases to a minimum and then perform the fully nonlinear viscous analysis of the hull forms to finalize the model. In the RANSE based optimization of Eefsen *et al.* (2004), the objective function is defined as a combination of total resistance at two speeds and an empirical relation between vertical motion response in head sea at three different speed.

4.3 Multi Objective Genetic Algorithm (MOGA)

As shown in the previous section, it is essential to use an algorithm capable of determining the global solution for hull optimization problems. In this study, the genetic algorithm is employed in the optimization framework. Genetic algorithms, which attempts to mimic the evolutionary principles observed in the nature, are based on the theory known as “Survival of the fittest.”In other words, an initial population is allowed to evolve, keeping only a few elite member in each generation and cross breeding them for desired properties with some level of mutation, which results in an overall increase of fitness in the population after few generations. In design optimization perspective, the initial population (or the first generation) is generated using stochastic uniform sampling within the allowable range for each free variable. The fitness of each individual design (hull form) is measured based on user defined objective functions. From this population, some elite members with the highest fitness value are chosen for next iteration, some of their variables are interchanged to generate new designs (cross breed) and new variable values introduced by means of mutation. The population count is generally kept constant per generation by adding random new members, which allows the algorithm to efficiently explore the whole design space.

The practical problems such as the ship hull optimization often requires minimization of multiple objective functions. This problem is called multi-objective optimization problem which can be mathematically described as

$$\begin{aligned}&\text{minimize } f(\boldsymbol{x},\boldsymbol{p}) = (f_1(\boldsymbol{x},\boldsymbol{p}), f_2(\boldsymbol{x},\boldsymbol{p}), f_3(\boldsymbol{x},\boldsymbol{p})\dots f_N(\boldsymbol{x},\boldsymbol{p}))\\&\text{subjected to constraints } g_j(\boldsymbol{x},\boldsymbol{p}) \geq 0\,(j=1,2,\dots,l)\end{aligned} \tag{2}$$

Commonly, the solution of a multi-objective optimization is presented as a Pareto front. The Pareto front or Pareto optimal is defined in Coello *et al.* (2007) as: *A solution* $x \in \Omega$ *is said to be Pareto Optimal if and only if there is no* $x^* \in \Omega$ *for which* $v = f_{x^*}$ *dominates* $u = f_x$.That is, x is called a Pareto Optimal if there is no other point x^* in the feasible domain Ω that reduces at least one objective function without increasing the other.

In this study, as the constraints are derived based on simulation results, the capability of solving the optimization problem with nonlinear constraint is necessary. At the moment, the optimization problems with multiple objectives and nonlinear inequality constraints can only be solved using the Multi-Objective Genetic Algorithm (MOGA) among available methods in the GOT in MATLAB®. Therefore, this method is applied in the developed optimization framework.

4.4 Automated optimization framework

Apart from having the three major components required for optimization (i.e., CAD modeler, Hydrodynamic solver and Optimization solver), it is necessary to develop a framework that allows transfer of information from one to the other. The schematic of the framework used in this study is shown in Fig. 4. The optimization starts with initial design variable values set by the Genetic Algorithm (lower bound of the design variables range) which calls the automatic hull form generation and panelization scripts. This is followed by hydrostatic and hydrodynamic calculations where the vessel speed is set based on selected Froude number $\left(Fn = U/\sqrt{gL}\right)$ and the radius of gyrations are calculated using standard approximations for ship hull (Faltinsen 1993).

$$\begin{aligned}k_{xx} &= 0.40 \times B\\k_{yy} = k_{zz} &= 0.25 \times L\end{aligned} \tag{3}$$

The objective function and constraints, also known as the measure of merit, are derived using both geometric and hydrodynamic analysis results. Here, the measure of merit is defined using two criteria: the vertical acceleration at the bow of the vessel in head sea condition at $Fn = 0.25$ and the wetted surface area. The vertical bow acceleration represents the comfort and safety of the vessel at sea while the wetted surface area is connected with the skin friction on the vessel. As reduction in the both parameters is desired, it is found from the multi objective optimization study that after certain point a reduction in one can only be achieved by compromising the other. The set of such results for the design variables are represented as a Pareto frontier. As there is not a single solution, the optimization loop continues to develop such Pareto frontier until a convergence criteria, such as number of generations or improvement in objective function, is met. This way the Pareto front allows the designer to understand the relative advantage of selecting one design value to other and make an informed decision.

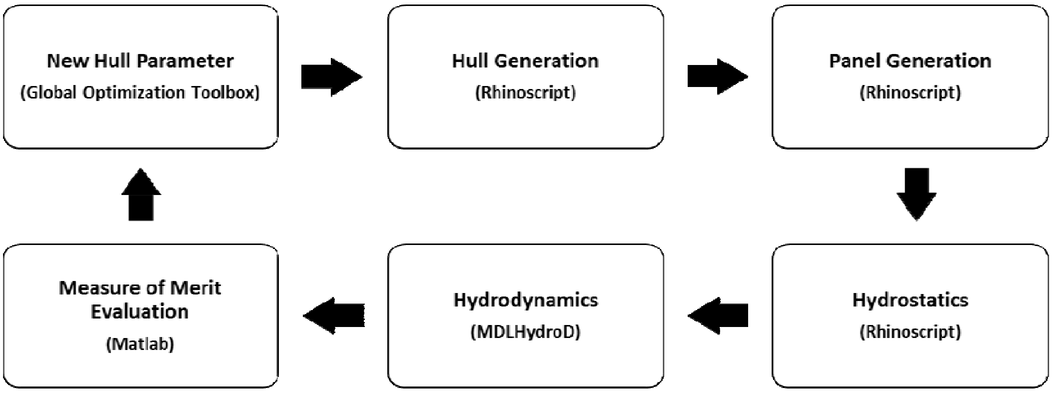


Fig. 4 The optimization framework

5. Results

The optimization was performed by considering variables numbered 19-25 in Table 1 as free variables. The lower and upper bounds for each of these variables are listed in Table 2. The displaced volume of the vessel is set to be within 2% of a given value, which is the constraint of the optimization. The objective function used are the wetted surface area and acceleration at the bow. The Multi Objective Genetic Algorithm is used with population size of 50 per iteration and up to 7 generations. An adaptive mutation factor is used for better convergence of the results. A total of 474 vessels were analyzed among which some were discarded due to not satisfying the displacement constraint. Finally, a Pareto front representing 18 hull forms with comparative advantage between two objective functions were obtained.

Table 2 Lower and upper bounds used in free variables

Si #	Free Variable	LB	UB
1	ParallelMidshipI	20	40
2	ParallelMidshipII	41	52
3	ParallelMidshipIII	53	60
4	FlatOfSideI	61	70
5	FlatOfSideII	71	90
6	FwdShoulder	91	102
7	BowContour	103	112

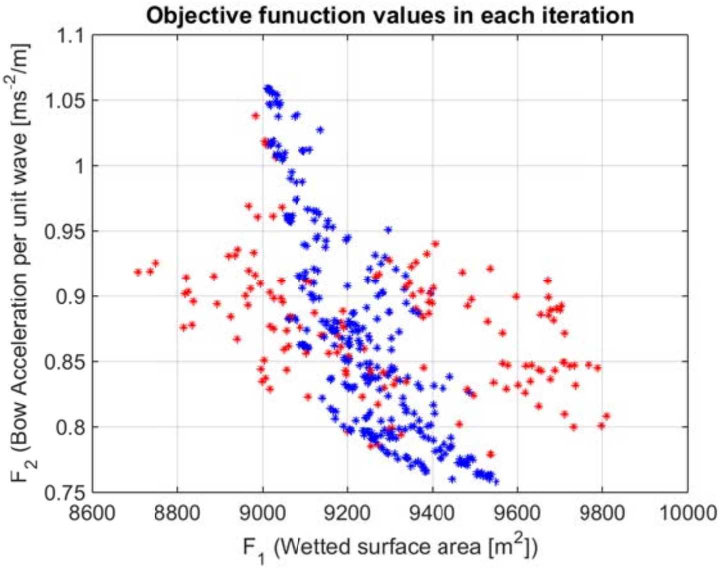


Fig. 5 Objective function values at each iteration

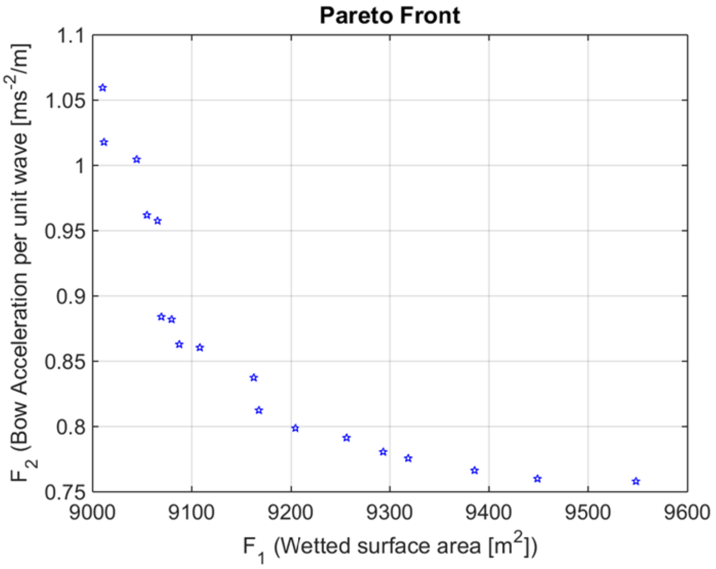


Fig. 6 Pareto front representing the best compromise between two objectives

In Fig. 5, the value of the objective function evaluated for each individual hull form is shown. The red markers represent hull forms that didn’t satisfy the displacement constraints and hence discarded. The blue markers represent the cases where the constraint was satisfied. A line can be drawn from the left enclosing the values representing the Pareto front. These values, constituting the Pareto front, are shown in Fig. 6.

5.1 Comparison of initial hull with optimized hull

To demonstrate the variability in performance due to only changes in lateral position of the section curves, the initial hull, which is set by the Genetic Algorithm as the lower bound of each parameters, is compared with the optimized hull. Figs. 7-9 shows the comparison between the initial and optimized hull for heave, pitch and acceleration at the bow of the ship respectively. All three figures show a significant improvement at the resonance frequency and for the larger wavelengths. The added resistance is also compared for both hull forms in Fig. 10, however since it was not considered in the optimization, no significant improvement can be seen in the large wavelength range.

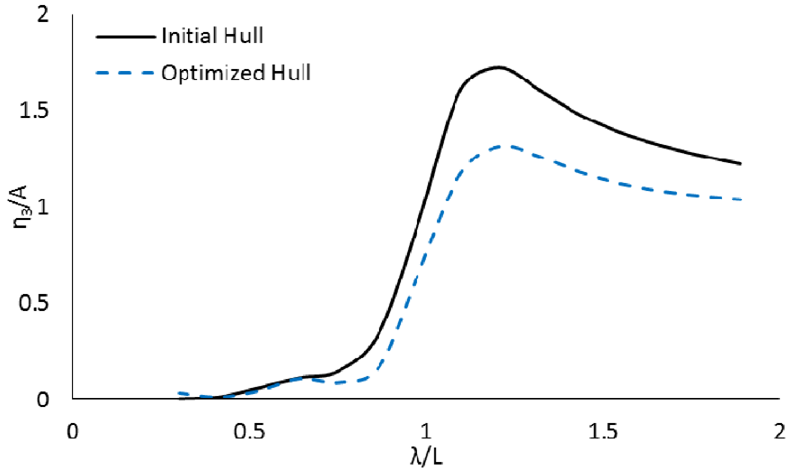


Fig. 7 Heave amplitude comparison between initial and optimized hull

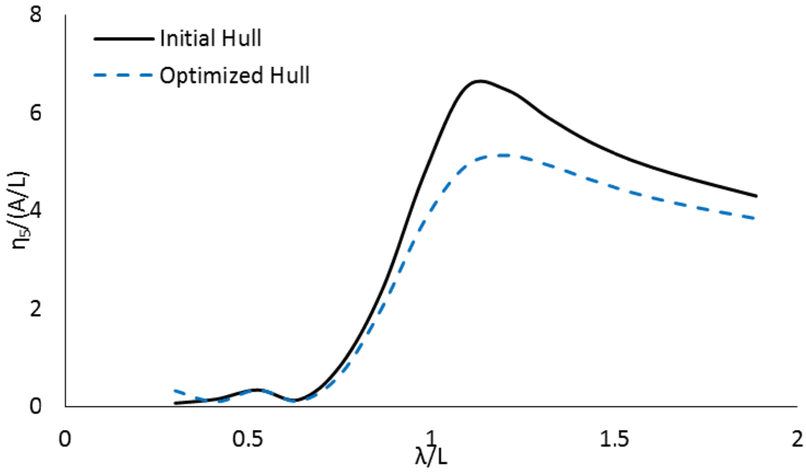


Fig. 8 Pitch amplitude comparison between initial and optimized hull

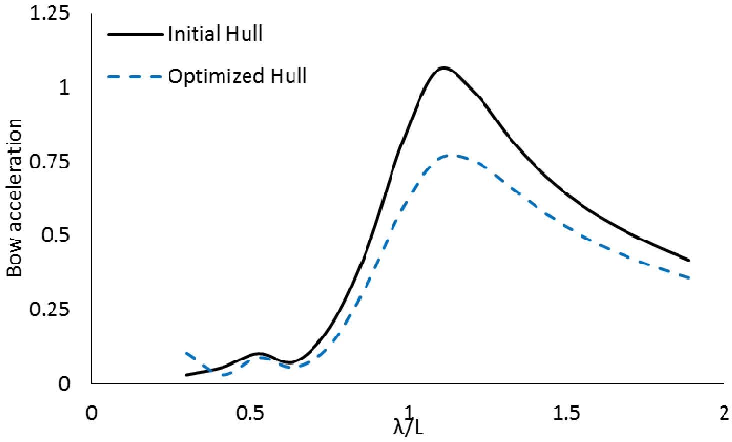


Fig. 9 Bow acceleration comparison between initial and optimized hull

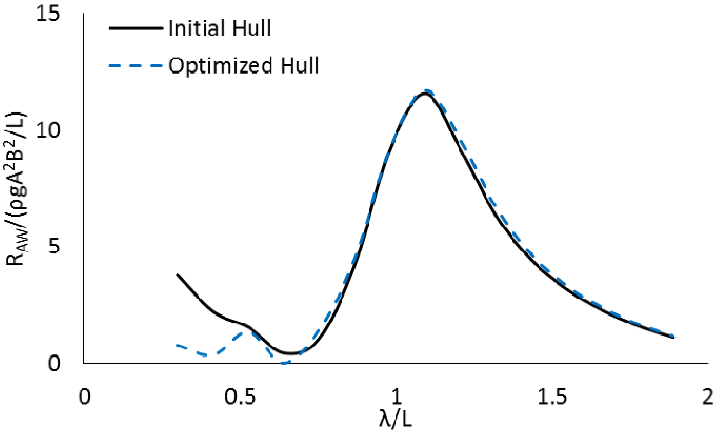


Fig. 10 Added resistance comparison between initial and optimized hull

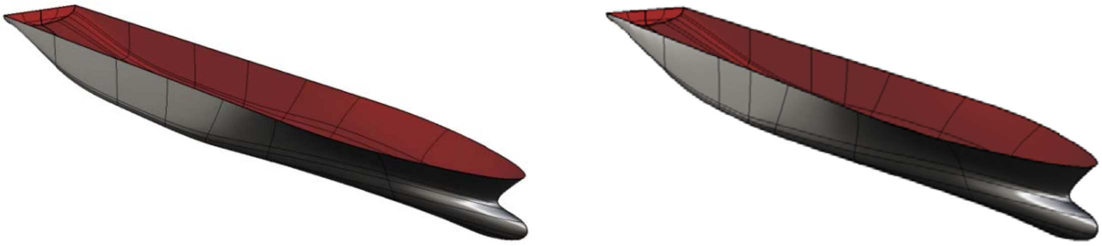

(a)
(b)

Fig. 11 Initial hull (a) and optimized hull (b) showing significant improvement in the bow region

A visual comparison of the initial hull and the optimized hull is shown in Fig. 11, where significant improvement in the bow region can be observed.

5.2 Comparison with commercial vessel KCS

The parametric hull is fitted to the commercial vessel KRISCO Container Ship (KCS) approximately by a surface comparison. The goal of this exercise was to see by varying the sectional line positions within significantly large range, whether it is possible to obtain similar performance after the optimization. Fig. 12 shows the overlapped surface comparison between the parametric hull and the commercial ship KCS.

The comparison of motion properties between the optimized hull form and the commercial KCS hull is presented in Figs. 13-15. It is clear from the results that the optimization procedure was able to produce a hull form with similar or for some aspects even better seakeeping performance compared to the commercial hull. An initial assessment of the optimized hull form from Fig. 16 suggests that the hull line at the fore part is pushed outward making the hull more blunt, while the midship and aft sections are made more slender. Unfortunately, this behavior is expected to be reversed when a resistance criterial is added to the optimization and hence it is important to perform optimization with both seakeeping and resistance together. This aspect of the optimization is currently being studied and will be presented in subsequent publications. The presented optimization process may be more relevant for FPSO and FLNG for which motion is more important and resistance is not a concern.

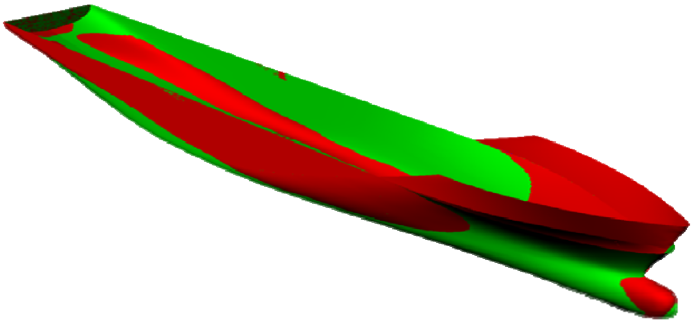


Fig. 12 The parametric hull (green) fitted to the commercial ship KCS (red)

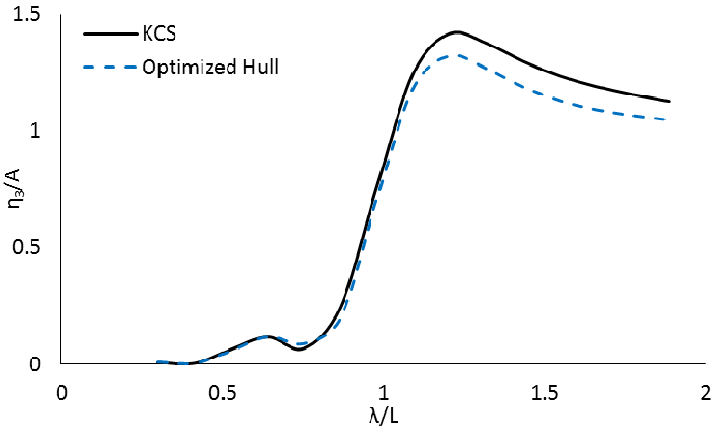


Fig. 13 Heave amplitude comparison between KCS and optimized hull

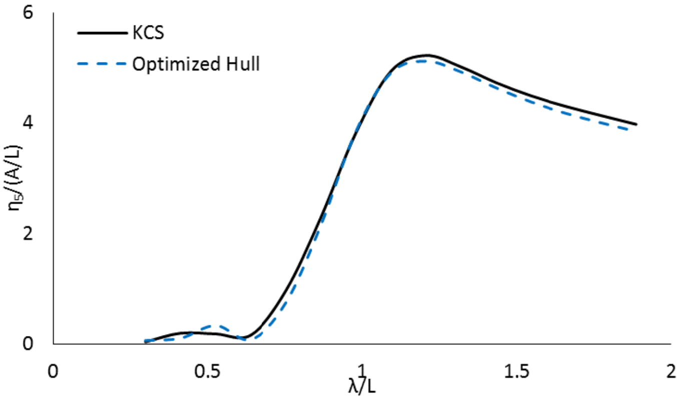


Fig. 14 Pitch amplitude comparison between KCS and optimized hull

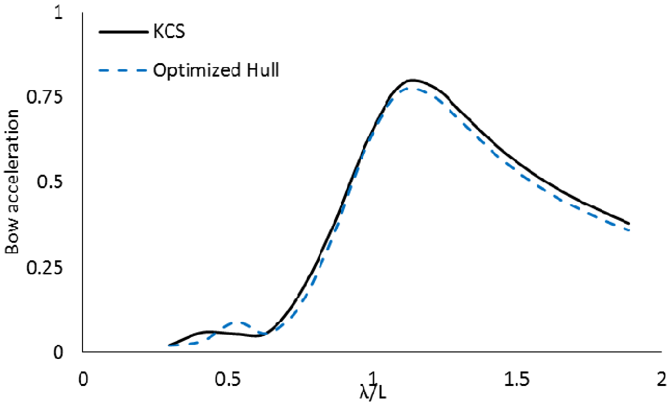


Fig. 15 Bow acceleration comparison between KCS and optimized hull

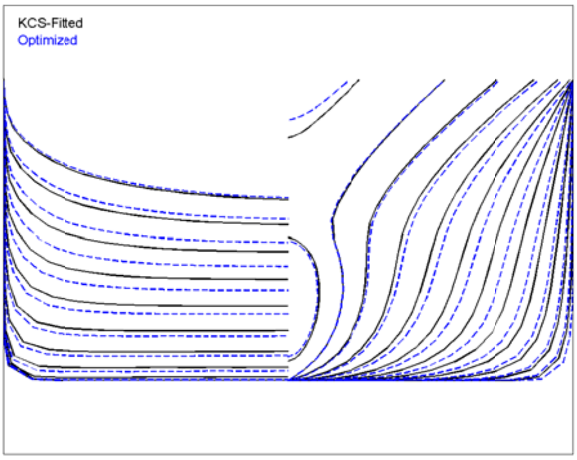


Fig. 16 Body plan of initial KCS fitted hull form compared to the optimized hull

6. Conclusions

Hull form optimization was identified as one of the major areas in ship transportation system where significant improvement can be achieved in terms of fuel economy, CO_2 emission and safety at the sea. In this study three separate technical areas: computer-aided design, computational hydrodynamics and optimization, were investigated and corresponding modeling and analysis tools have been developed and integrated in an optimization framework. The key findings from the study can be summarized as:

1. A practical geometry modeling method is the first step of any optimization procedure. Here, a B-Spline curve based ship model parameterized using common naval design terms is developed using Rhinoscript. In this approach, it is relatively easy to know the bounds of each variable which would produce a mutually non-intersecting surface and the fairness of the hull is automatically ensured.
2. In order to investigate a large number of hull forms, it is essential to have a robust, accurate and time efficient numerical tool for the hydrodynamic analysis. An in-house tool MDL-HydroD has been developed with consideration of factors beneficial in optimization process. Specifically, only the underwater hull surface needs to be discretized (i.e., no free surface required), and 3D frequency domain analysis is very time efficient and more accurate than strip theory methods.
3. A number of optimization algorithms were investigated and the non-gradient based algorithms were found to be best suited for the ship hull optimization purposes. The MATLAB® Global Optimization Toolbox is utilized in this study to complete the optimization framework, which allows selection of a number of optimization algorithms. The Multi Objective Genetic Algorithm (MOGA) is employed to optimize a ship hull for the seakeeping performance enhancement where a large number of hull forms were analyzed and a Pareto front representing best achievable performance for two competing objectives is obtained.
4. Significant improvement in the heave, pitch and acceleration at the bow of the ship is achieved compared to the initial hull form. The optimized hull form is then compared with an equivalent commercial ship hull, where a close agreement between the performances of the two hull forms were found.

In conclusion, the optimization framework provides a way of quick hull form assessment for multiple performance criteria. For a more formal optimization procedure, the seakeeping performance evaluation criteria needs to consider multiple wave headings, speed, irregular seaway and number of slamming events. Apart from this, the minimization of wave resistance also needs to be considered. These modifications and validations are currently in progress.

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References

Bagheri, H., Ghassemi, H. and Dehghanian, A. (2014), “Optimizing the seakeeping performance of ship hull forms using genetic algorithm”, *TransNav, Int. J. Mar. Navig. Saf. Sea Transp.*, **8**(1), 49-57. doi:10.12716/1001.08.01.06

Biliotti, I., Brizzolara, S., Viviani, M., Vernengo, G., Ruscelli, D., Guadalupi, D. and Manfredini, A. (2011), “Automatic parametric hull form optimization of fast naval vessels”, *Proceedings of the FAST 2011 11th International Conference on Fast Sea Transportation.* Honolulu, Hawaii.

Birk, L. and Clauss, G.F. (2008), “Optimization of offshore structures based on linear analysis of wave-body interaction”, *Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering.* Estoril, Portugal.

Campana, E., Peri, D., Tahara, Y. and Stern, F. (2006), “Shape optimization in ship hydrodynamics using computational fluid dynamics”, *Comput. Method. Appl. M.*, **196**(1-3), 634-651. doi:10.1016/j.cma.2006.06.003

Clauss, G.F. and Birk, L. (1996), “Hydrodynamic shape optimization of large offshore structures”, *Appl. Ocean Res.*, **18**(4), 157-171. doi:10.1016/S0141-1187(96)00028-4

Coello, C.A.C., Lamont, G.B. and Veldhuizen, Da. Van (2007), *Evolutionary Algorithms for Solving Multi-Objective Problems*, (2nd Ed.), Springer, New York.

Eefsen, T., Walree, F. Van, Peri, D., Terwisga, P. Van, Kristensen, H.O., Dattola, R. and Visser, M. (2004), “Development of frigate designs with good seakeeping characteristics”, *Proceedings of the 9th Symposium on Practical Design of Ships and Other Floating Structures.* Luebeck-Travemuende, Germany.

Faltinsen, O. (1993), *Sea Loads on Ships and Offshore Structures*, Cambridge University Press, Cambridge, England.

Grigoropoulos, G.J. and Chalkias, D.S. (2010), “Hull-form optimization in calm and rough water”, *Comput. Des.*, **42**(11), 977-984. doi:10.1016/j.cad.2009.11.004

Guha, A. (2012), *Development of a Computer Program for Three Dimensional Frequency Domain Analysis of Zero Speed First Order Wave Body Interaction*, MS Thesis, Ocean Eng. Texas A&M University, College Station, TX.

Guha, A. and Falzarano, J. (2015a), “Estimation of hydrodynamic forces and motion of ships with steady forward speed”, *Accept. Int. Shipbuild. Prog.*, 1-38.

Guha, A. and Falzarano, J. (2015b), “The effect of hull emergence angle on the near field formulation of added resistance”, *Accept. Ocean Eng.*, 1-27.

Guha, A. and Falzarano, J.M. (2013), “Development of a computer program for three dimensional analysis of zero speed first order wave body interaction in frequency domain”, *Proceedings of the ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering*. Nantes, France.

Harries, S. and Valdenazzi, F. (2001), “Investigation on optimization strategies for the hydrodynamic design of fast ferries”, *Proceedings of the 6th International Conference on Fast Sea Transportation.* Southampton.

Heimann, J. (2005), *CFD based optimization of the wave-making characteristics of ship hulls*, PhD Dissertation, Technical University Berlin, Berlin, Germany.

Kim, H. (2009), *Multi-objective optimization for ship hull form design*, PhD Dissertation, George Mason University, Fairfax, Virginia.

Kostas, K.V., Ginnis, A.I., Politis, C.G. and Kaklis, P.D. (2015), “Ship-hull shape optimization with a T-spline based BEM–isogeometric solver”, *Comput. Method. Appl. M.*, **284**, 611-622. doi:10.1016/j.cma.2014.10.030

Kükner, A. and Sariöz, K. (1995), “High speed hull form optimisation for seakeeping”, *Adv. Eng. Softw.*, **22**(3), 179-189. doi:10.1016/0965-9978(95)00016-P

Maisonneuve, J.J., Harries, S., Marzi, J., Raven, H.C., Viviani, U. and Piippo, H. (2003), “Towards optimal design of ship hull shapes”, *Proceedings of the 8th International Marine Design Conference.* Athens.

Peltzer, T.J., Rosenthal, B.J., Reppun, W.K., Kring, D.C., Milewski, W.M. and Connell, B. (2008), "Multi-body seakeeping design optimization", *Proceedings of the 8th International Conference on Hydrodynamics.* Nantes, France.

Petersen, G., Goris, B., Shapiro, P., Oers, B. van and Rouzic, J. le. (2009), Grasshopper parametric ship hull modeling [WWW Document]. Rhinoceros Rep. URL http://rhinocentre.blogspot.com/2009/12/grasshopper-parametric-ship-hull.html

Sariöz, E. (2009), "Inverse design of ship hull forms for seakeeping", *Ocean Eng.*, **36**, 1386-1395. doi:10.1016/j.oceaneng.2009.08.011

Smith, T.C., Walden, D.A. and Thomas-III, W.L. (1990), *Improvement of destroyer performance through optimized seakeeping design (No. DTRC-92/001),* Bethesda, Maryland.

Somayajula, A., Guha, A., Falzarano, J., Chun, H. and Jung, K.H. (2014), "Added resistance and parametric roll prediction as a design criteria for energy efficient ships", *Ocean Syst. Eng.*, **4**(2), 117-136. doi:10.12989/ose.2014.4.2.117

Tahara, Y., Peri, D., Campana, E.F. and Stern, F. (2011), "Single- and multiobjective design optimization of a fast multihull ship: numerical and experimental results", *J. Mar. Sci. Technol.*, **16**, 412-433. doi:10.1007/s00773-011-0137-y

White, R.D. (2010), Ocean shipping lines cut speed to save fuel costs [WWW Document]. Los Angeles Times. URL http://articles.latimes.com/2010/jul/31/business/la-fi-slow-sailing-20100731