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Hydrodynamic multidisciplinary optimization of a container ship and its propeller using comprehensive HPSOP code

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Abstract

Hydrodynamic shape optimization plays an increasingly important role in the shipping industry. To optimize ship hull and propeller shapes for minimum total (friction+wave) calm-water resistance and maximum open water efficiency, respectively, the main particulars of a hull and propeller model are considered as design variables. The optimization problem is performed by using an integrated hull-propeller system optimization problem (HPSOP) code in a multi-level and multi-point methodology in early-stage ship design. Three numerical methods with variable fidelity are employed to carry out the hydrodynamic performance analysis of a ship's hull and propeller. A ship and its propeller are selected as initial models to illustrate the effectiveness of the proposed optimization procedure. The numerical results show that the developed technique is efficient and robust for hydrodynamic design problems.

Nomenclature

L: Length of ship
B: Breadth of ship
d: Draft of ship
D: Propeller diameter
Z: Number of blades of the propeller
P/D: Pitch-diameter ratio of propeller
EAR: Expanded area ratio of propeller
Fn: Froude number
Rt: Ship total resistance
T: Propeller thrust
Q: Propeller torque
Kt: Thrust coefficient ($Kt = T/\rho n^2 D^4$)
Kq: Torque coefficient ($Kq = Q/\rho n^2 D^5$)
Eta: Propeller efficiency ($Eta = J \cdot Kt/2\pi Kq$)
J: Advance coefficient ($J = V_A/nD$)
N: Propeller rotating speed in RPM
n: Propeller rotating speed in RPS (= RPM/60)
V_A: Advance velocity
P_O: Atmospheric pressure
P_V: Vapor pressure
K: Keller's coefficient ($0 < K < 0.2$)

Introduction

The conventional maritime industry approach is to optimize hull resistance and propeller performance separately. A ship's hull resistance is minimized by a naval architect and the propeller thrust is maximized for a given power by the propeller's designer. Once both the designs (hull and propeller) are combined, the actual performance of the system is found. The ultimate list of all the largest container ships in the world is presented online (Wikipedia, 2018). There, the names of their owners – the world's largest container shipping line companies – can be seen. Details of one particular container ship (14,000 TEU) are as follows and are close to those of our case study container ship: Main engine power output: 72,240 KW, Speed: 22 kn, Draft: 16 m, Breadth: 51 m, Overall Length: 352 m, DWT: 165,887 tons. Figure 1 shows a model of the container ship.

Figure 1. Model of container ship

Two main parts of a ship system which have a significant effect on the ship's total efficiency are its hull and propeller, thus it is necessary to optimize the effective parameters of the propeller and hull using a comprehensive numerical approach. Numerical techniques play a key role in the analysis of the flow field around ship's hull and propeller, especially in hydrodynamic shape optimization, because they are potentially an appropriate replacement for towing tank experiments. It is worth noting that the hull-propeller system optimization problem (HPSOP) code usually requires a large number of evaluations; thus, selecting a less time-consuming and accurate numerical method is very important. In the early stages of a multi-objective optimization problem (MOP) the design space is large; as the optimization algorithm progresses and approaches an optimal design area the design space becomes smaller. Therefore, using a fast numerical method with relatively good accuracy in the initial steps, and a more accurate one in the final stages of the optimization problem, is a rational way to find optimal designs.

Determination of the hydrodynamic characteristics of a ship's hull and propeller using computational fluid dynamics (CFD) techniques is one of the most important topics in naval architecture for computing ship performance in different operating conditions. Among different CFD methods, the thin-ship theory of Michell is a simple and fast approach and the boundary element method (BEM) is a more accurate but more time-consuming method than the former. These two potential-based hydrodynamic solvers can respectively be applied in the conceptual and preliminary design phases of ship system. Simultaneously, optimization of a ship's hull and propeller by using the two different fidelity solvers is more efficient than the conventional approach of utilizing just one. The scope of this study is to develop a bi-level and bi-objective optimization code for the hydrodynamic design of container ships propelled by their propeller(s) as a combined system at two operating points.

Hydrodynamic optimizations of ship hulls and propellers as two independent systems have been carried out by many researchers. Genetic algorithm (GA) and Michell's theory were used by Day and Doctors (Day & Doctors, 1997) to find the minimum total resistance of a mono-hull and catamaran. In another work, Michell's theory and evolution strategy were respectively applied as a wave resistance estimator and an optimization algorithm in the optimization problem of a Series 60 hull form in calm water (Zakerdoost, Ghassemi & Ghiasi, 2013). A GA based optimization technique and the well-known Dawson panel method were employed in research to optimize a ship's hull form from a resistance point of view (Dejhalla, Mrša & Vuković, 2002). Zhang et al. (Zhang, Ma & Ji, 2009) applied nonlinear programming to minimize the wave resistance of the bow-body shape of an S60 hull evaluated by the Rankine source method. A double-chine, planing hull form optimization was implemented in another study using evolutionary strategies with respect to hull performance in calm and rough waters (Grigoropoulos & Chalkias, 2010). Other researchers (Jeong & Kim, 2013; Park, Choi & Chun, 2015; Kim, Choi & Chun, 2016) have also worked on the hydrodynamic optimization of ship's hull form using potential flow solvers and optimization algorithms. The efficiency of a self-twisting composite propeller was maximized by Pluciński et al. (Pluciński, Young & Liu, 2007) using a GA and BEM/finite element method (FEM) solver. Benini (Benini, 2003) proposed a multi-objective evolutionary algorithm to optimize a B-series propeller, while the open water performance was calculated using regression formulas. A program was developed by Burger (Burger, 2007) to analyze propeller performance by using the vortex lattice model based on GA. Gaafary et al. (Gaafary, El-Kilani & Moustafa, 2011) presented a design optimization technique for B-series marine propellers to optimize their hydrodynamic performance (objective functions) at a single speed. In another work, a multi-objective optimization program was proposed to maximize efficiency and thrust coefficient by applying polynomial expressions and NSGA-II (Xie, 2011). A multi-objective Particle Swarm Optimization was developed to maximize the efficiency and minimize the cavitation of marine propellers by using analytical and polynomial expressions (Mirjalili, Lewis & Mirjalili, 2015). NSGA-II was applied to a propeller optimization problem by utilizing the BEM/FEM technique (Jiang et al., 2018). A hull-propeller system optimization was performed to minimize lifetime fuel consumption by using blade element theory, Michell's theory and the NSGA-II algorithm (Ghassemi & Zakerdoost, 2017). A mathematical model of the external forces operating on a vessel and an algorithm to solve the problem for calculating the instantaneous speed of the vessel in selected weather conditions were proposed by Szelangiewicz et al. (Szelangiewicz, Wiśniewski & Żelazny, 2014). Moreover, a parametric model of a ship's propulsion system (screw propeller–propulsion engine) as well as a method, based on both the resistance and propulsion system models, of calculating the mean statistical value of a ship's service speed under seasonal weather conditions occurring on shipping lines were presented in research by Szelangiewicz and Żelazny (Szelangiewicz & Żelazny, 2015).

The main goal of this research is to present an efficient tool (HPSOP code) for optimization of ship hull-propeller systems in the conceptual/preliminary stage of ship design. A well-known optimization algorithm integrated with two different fidelity methods in a multi-level procedure is used to minimize total ship resistance and maximize open water propeller efficiency. The remainder of this study is organized as follows: the forthcoming section briefly describes the different parts of the HPSOP code, including a numerical solver, geometry representation and optimization algorithm. Next section presents a multi-level optimization strategy. Later, we present a case study on a container ship driven by a well-known propeller and the results are discussed. Finally, some conclusions are drawn.

Analysis and optimization techniques

Figure 2 shows a general scheme of the hydrodynamic optimization methodology. It comprises three major parts: first, a numerical technique used as an analysis tool to indicate the values of the hydrodynamic performances; second, a geometry modeling approach to provide a connection between design variables and body shape(s); and third, an algorithm to solve the nonlinear optimization problem composed of the objective and constraint functions.

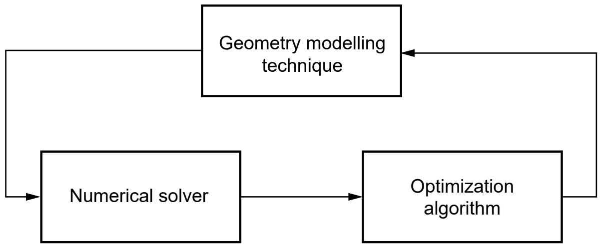

Figure 2. General flowchart of the basic parts of the hydrodynamic optimization algorithm

Numerical solver

The total calm-water resistance of a container ship and the open water efficiency of the propeller working behind it are our main hydrodynamic performance parameters in this study. Keller's inequality equation is one of the best known cavitation criteria for conventional marine propellers. This criterion may be used to obtain the expanded blade area required to avoid cavitation. The numerical solvers employed to evaluate the wave resistance component of ship's hull and hydrodynamic performance coefficients of a ship's propeller are integrated in a code of variable fidelity methods. The low-fidelity solvers are lifting line theory and Michell's theory and the medium-fidelity one is potential-based boundary element method (BEM). The mathematical relationships and validation of the numerical methods can be found in the authors' publications (Ghassemi, 2009; Ghassemi & Kohansal, 2010; Zakerdoost, Ghassemi & Ghiasi, 2013).

Geometry representation

Bezier and B-spline curves have a considerable shortcoming. They are polynomial-based and cannot accurately represent implicit conic shapes, such as circles, ellipses and hyperbolas; therefore, an extension of B-splines called Non-Uniform Rational B-Splines (NURBS) was introduced to overcome these shortcomings by using fractions of the same interpolation functions. Presently in computer aided design (CAD), NURBS is one of the most common geometric representation techniques. Because the NURBS approach inherits the benefits of B-splines, they exhibit excellent performance in curve manipulation; most CAD systems have utilized them as a powerful tool for generating curves and surfaces of complex geometries. The family of curves that can be represented with NURBS is much wider than that with B-Splines or Bézier curves and also includes conics. The algorithms associated with NURBS are easier to implement, and these algorithms, as evaluations of positions or derivatives, are stable and fast. In this paper NURBS are used to build up the curves and surfaces of the geometric models describing a ship's hull and propeller for allowing variation of their forms during the optimization process.

Optimization algorithm

Among the most well-known stochastic multi-objective optimization techniques is the Non-dominated Sorting Genetic Algorithm II (NSGA-II). NSGA II (Deb et al., 2002) was proposed to remove several deficiencies of the first version (NSGA) that included the high computational cost of non-dominated sorting, lack of elitism and lack of sharing parameters. Currently NSGA-II is famous for its low computational complexity, simplicity and its ability to maintain a good spread of solutions. The non-dominated sorting method is an important characteristic of NSGA-II. A general NSGA-II procedure to be implemented in a routing problem is presented in the following steps: 1) Initialize the population, 2) While the termination criterion is not met repeat the following: a) Evaluate each solution in the population by computing objective function values, b) Rank the solutions in the population using non-dominated sorting, c) Perform selection using the crowded binary tournament selection operator, d) Perform crossover and mutation (as in conventional GA) to generate the offspring population, e) Combine the parent and child populations, f) Replace the parent population with the best members (selected using non-dominated sorting and the crowded comparison operator) of the combined population, 3) Output the first non-dominated front of the population. A brief description of the optimization algorithm is given in Figure 3.

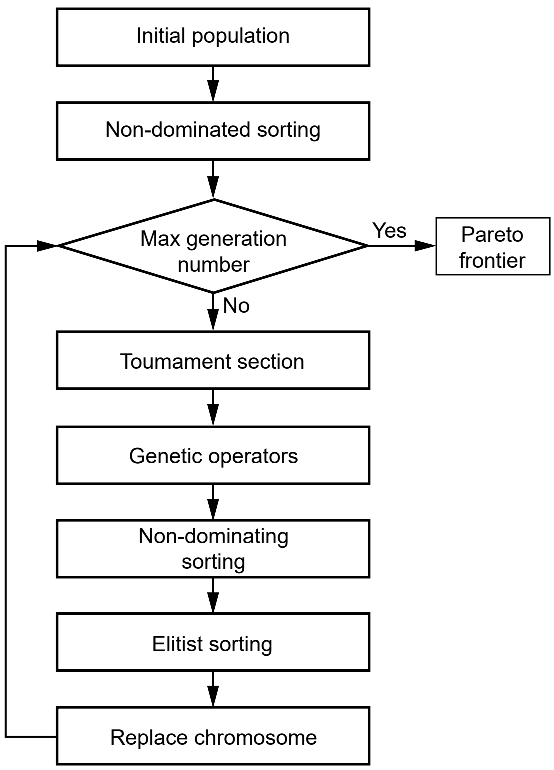

Figure 3. General schematic of NSGA-II algorithm

Multi-level optimization procedure

In an effort to reduce the overall computational cost of performing the multi-point optimizations and thereby make it more efficient, we use the multi-level optimization approach to solve a container ship system design problem. The optimization scheme is divided into two levels according to the variable-fidelity numerical methods. A flowchart of the hydrodynamic design procedure of HPSOP is detailed in Figure 4. The first step in carrying out the shape optimization is design space definition. The main variables significantly influencing the hydrodynamic performance of a HPS, i.e. ship length to beam ratio, beam to draft ratio, draft, propeller diameter, number of blades and pitch ratio have been selected as the design variables vector, $X = [L/B, B/d, d, D, Z, P/D]$. A Latin Hypercube Sampling (LHS) technique is used to perform the Design of Experiments (DOE) to generate the individuals. This technique can distribute the individuals throughout the given design space evenly. In this step, evaluation of the ship's hull resistance and propeller performance in calm water are carried out by using coupled Michell's theory and ITTC-57 correction line formula and lifting line theory respectively. The operating propeller revolution rate at the design condition is calculated from the intersection point of required and available propeller thrust coefficient curves (Ghassemi, & Zakerdoost, 2017). The other hydrodynamic performance parameters of the propeller are obtained at this point. For estimating wake fraction and the thrust deduction factor there exist some empirical formulas, from which two well-known formulas for single screw ships were selected. We took the formulas from the trial results of more than 150 ships and 65 tests performed respectively by Taylor and Schoenherr (Ghose, & Gokarn, 2004). The wake fraction is a function of the block coefficient and the thrust deduction factor is related to the wake fraction. The objective functions, which are a linear combination of the total hull resistance (f_1) and the propeller efficiency (f_2) at two operating conditions, are penalized by a penalty function if the design constraints of displacement (g_1) and diameter to draft ratio (g_2) are not satisfied. The HPSOP code will proceed to

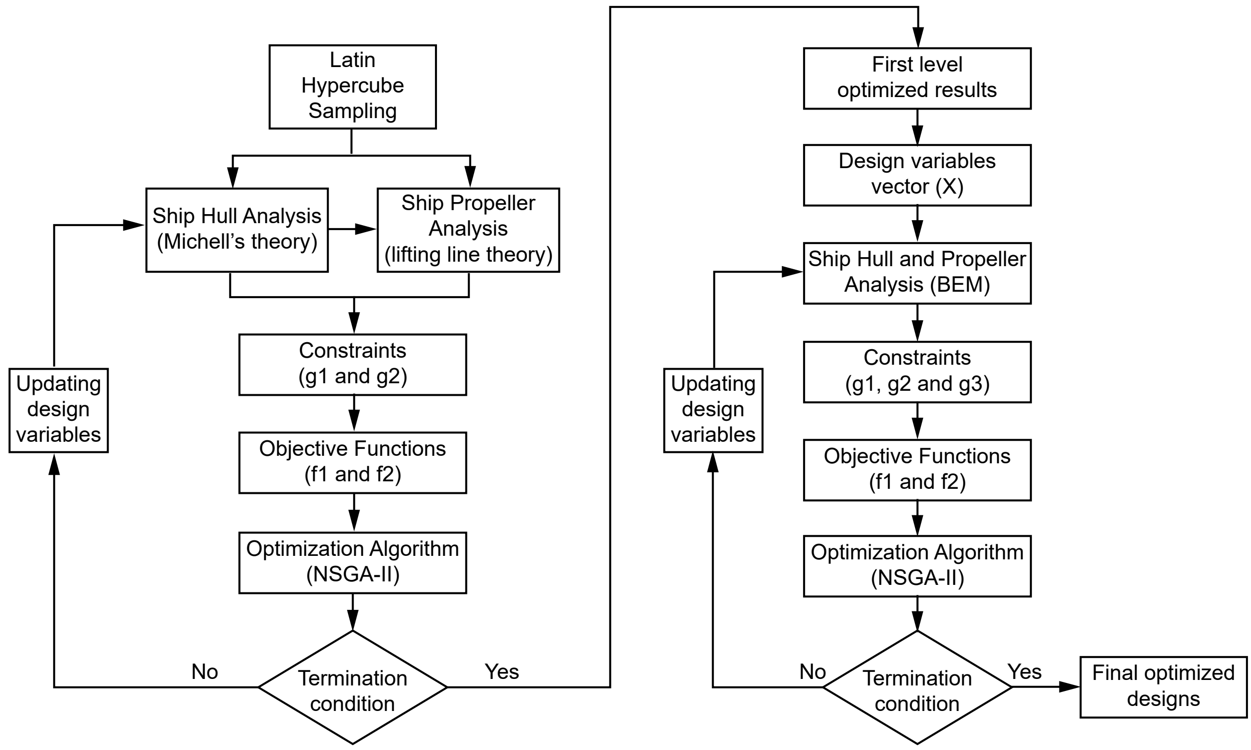

Figure 4. Comprehensive flowchart of the hydrodynamic design procedure of HPSO

the second level if one of the termination conditions is satisfied. The output generation of the first level is used as the input generation of the second one. In this level, the design space is small and we need to apply a higher fidelity tool, BEM, to evaluate hull-propeller systems (HPSs). In addition to the two constraints used in the first level, the Keller's cavitation criterion (g_3) is employed as a third design constraint. This process is repeated until it reaches the maximum generation and finally arrives at the Pareto front of optimal solutions. The formulation of HPSOP is as follows:
Minimize:

$$F(X)=[f_1(X), f_2(X)]^T, \quad X \in R^6 \tag{1}$$

where

$$f_1(X)=\sum_{i=1}^{2}\left(\frac{Rt}{RT_0}\right)_i; \quad f_2(X)=\sum_{i=1}^{2}\left(\frac{\eta_0}{\eta}\right)_i \tag{2}$$

Subject to:

$$\begin{aligned} g_1(X) &\equiv \left|\frac{\Delta-\Delta_0}{\Delta_0}\right| < 0.05 \\ g_2(X) &\equiv 0.55 \le \frac{D}{d} \le 0.75 \\ g_3(X) &\equiv \frac{(1.3+0.3Z)T}{(P_O-P_V)D^2}+K \le EAR \end{aligned} \tag{3}$$

Results and discussion

The present multi-objective optimization problem to find the minimum total resistance and the maximum open water efficiency was performed on a typical 14,000 TEU container ship, the Duisburg Test Case (DTC), propelled by the well-known single propeller DTMB P4119, as the initial ship system design. As already expressed, NSGA-II is used as an optimization algorithm. The system parameters of NSGA-II are as follows: crossover rate = 0.9, mutation rate = 0.05, population size = 50, maximum generation number = 150. The characteristics and operating conditions of the optimization problem are presented in Table 1. The upper and lower bounds of the design variables are depicted in Table 2. The Pareto-optimal front of the optimization problem in each generation and also the final Pareto front obtained in 150 generations are represented in Figure 5. The figure shows that NSGA-II can promote the spreading of individuals along the Pareto front. Thus, it can be concluded that the diversity of the algorithm, which is one of the main factors in multi-objective evolutionary algorithms, is appropriate. The horizontal and vertical axes show the objective functions f_1 and f_2 respectively.

Table 3 indicates the main characteristics of the initial design against five optimal designs which have been obtained by employing the NSGA-II algorithm.

Table 1. Characteristics of HPSOP

Parameters	Value
Hull type	DTC
Propeller type	P4119
1st operating condition	$Fn_1 = 0.22$
2nd operating condition	$Fn_2 = 0.27$
1st weight coefficient	$w_1 = 0.65$
2nd weight coefficient	$w_2 = 0.35$

Table 2. Limits of design variables vector

Parameters	Case: DTC-P4119	
Design variable	Lower limit	Upper limit
Number of blades	3	7
Pitch ratio	0.95	1.05
Propeller Diameter[m]	8.5	9.5
Draft[m]	14	14.5
Breadth to Draft ratio	3.0	4.5
Length to Breadth ratio	6.5	8.5

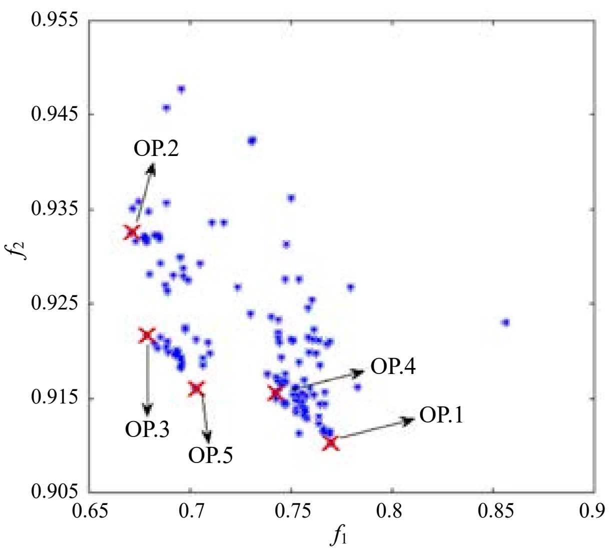

Figure 5. Evolution of the Pareto fronts during DTC-P4119 HPSOP

Table 3. Characteristics of the initial and optimal designs for DTC-P4119 HPSOP

	L [m]	B [m]	d [m]	C_B	Z	D [m]	P/D	f_1	f_2
IS	355.00	51.04	14.50	0.661	3	9.00	1.00	1.00	1.00
OP1	362.43	43.35	14.03	0.751	4	9.45	0.95	0.77	0.910
OP2	362.46	44.15	14.15	0.733	5	9.37	1.02	0.67	0.933
OP3	370.45	43.58	14.15	0.728	5	9.45	0.97	0.68	0.922
OP4	364.70	44.10	14.18	0.745	4	9.41	0.98	0.74	0.915
OP5	366.23	43.55	14.09	0.742	5	9.38	1.05	0.70	0.916

Among the main dimensions of the optimized hulls, the breadth and draft values have decreased in comparison to those of the initial hull. The hull length and block coefficient have increased. As can be seen, the variations of the optimized hull dimensions are such that the total hull resistance reduces while the ship's displacement remains unchanged. The table also illustrates that the number of propeller blades and the propeller diameter of the optimal designs are larger than those of the initial one but the pitch ratio has not changed significantly. As was expected, these changes in hull and propeller geometries have improved the values of the objective functions. Figures 6 and 7 show the wave-making resistance and

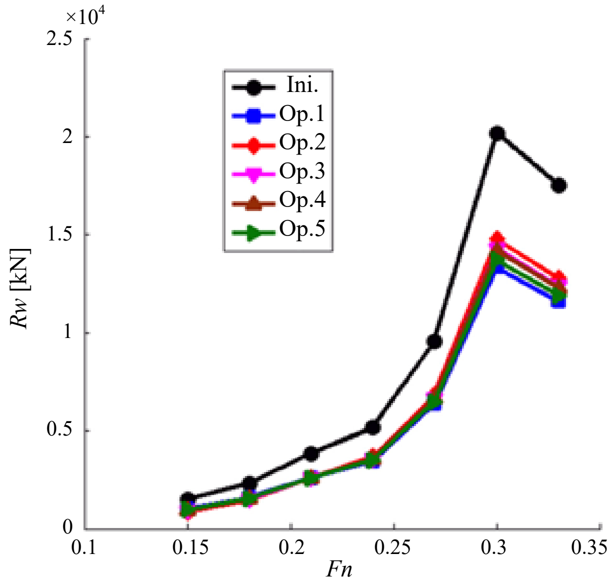

Figure 6. Wave-making resistance of the optimized hulls for DTC-P4119 HPSOP

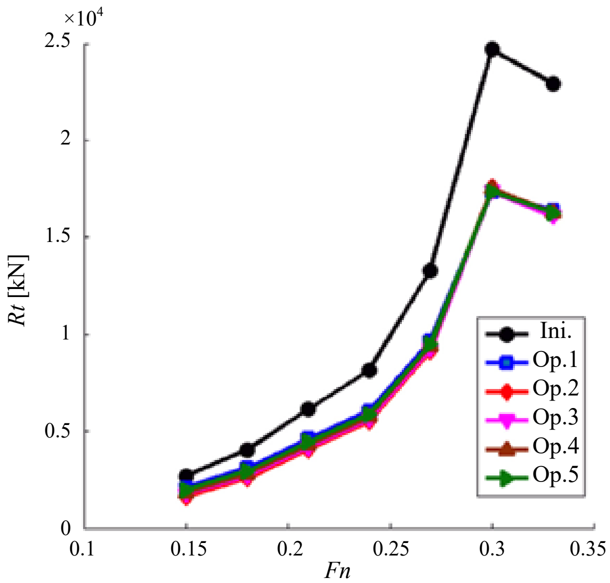

Figure 7. Total resistance of the optimized hulls for DTC--P4119 HPSOP

total resistance of the initial and optimized solutions versus Froude number. As can be seen from these figures, the wave-making resistance and total resistance of the optimized solutions are significantly lower than those of the initial one at all values of Froude number, including the operating speeds. The remarkable increase in the optimal length to breadth ratio confirms the decrease in the hull wave-making and totals resistances shown in Figures 6 and 7.

Figure 8 compares the hydrodynamic performance of the initial and optimized propellers for DTC-P4119 HPSOP. The open water efficiency of all the optimized propellers is relatively larger than that of the initial one at most advance coefficients which means the optimized propellers produce a higher thrust value than the initial one for a given torque. The changes in propeller diameter, number of blades and pitch ratio lead to these results. In other words, the increase in the diameter has a relatively stronger influence on the hydrodynamic performance of the propeller than a decrease in pitch ratio and increase in number of blades.

It is worth noting that all the optimized HPSs on the Pareto front (as shown in Figure 3) are candidates for the designers' final choice. Selection of the final HPS is based on the designers' conditions. In this paper, from the final optimal results, we choose one HPS, called compromise solution, by using a decision-making technique. In this technique, the objective functions are normalized and then the solution which has the minimum distance to the utopia point is selected as the best optimal solution (Ghassemi, & Zakerdoost, 2017). Based on this technique, the individual OP3 is the final optimal or compromise solution. If diagrams of the required and available thrust coefficients are drawn at the two design Froude numbers we get two intersection points for each of the initial and compromise solutions. These two intersection points, J_1 and J_2, and the hydrodynamic performance of the hulls and propellers at these points are reported in Table 4. As can be seen from the table, the advance coefficients of the compromise solution have been increased compared to those of the initial one which indicates getting closer to the location of

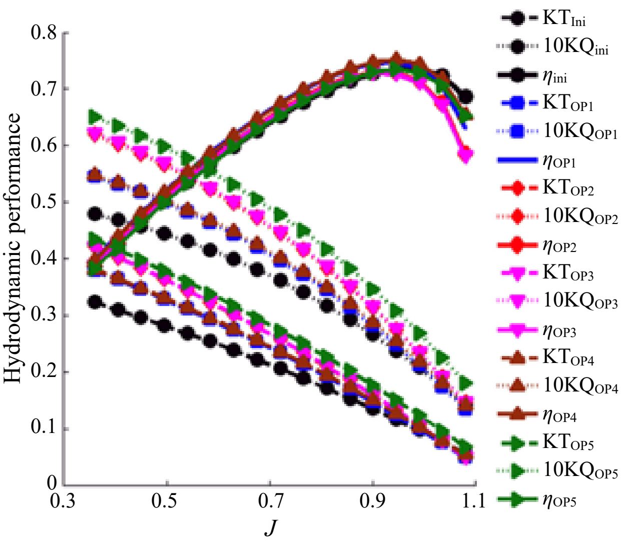

Figure 8. Open water performance of initial and optimized propellers for DTC-P4119 HPSOP

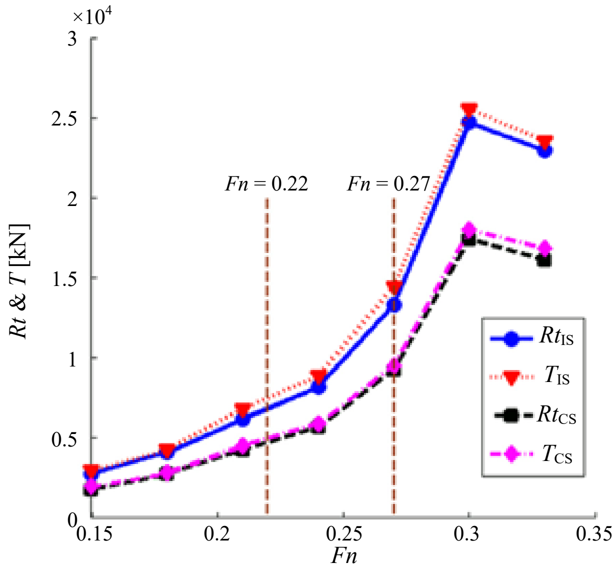

Figure 9. Hull resistance and propeller thrust of initial and compromise solutions

Table 4. Characteristics of initial and compromise designs for DTC-P4119 HPSOP

Initial design				Compromise design			
Fn_1	0.22	Fn_2	0.27	Fn_1	0.22	Fn_2	0.27
Rt_1[N]	5764439	Rt_2[N]	13273775	Rt_1[N]	3940328	Rt_2[N]	9218147
J_1	0.648	J_2	0.558	J_1	0.774	J_2	0.684
N_1 [RPM]	98.69682	N_2 [RPM]	140.6647	N_1 [RPM]	76.27231	N_2 [RPM]	105.9236
Kt_1	0.232305	Kt_2	0.262911	Kt_1	0.230096	Kt_2	0.275562
$10Kq_1$	0.39259	$10Kq_2$	0.42511	$10Kq_1$	0.411433	$10Kq_2$	0.468943
Eta_1	0.610257	Eta_2	0.549242	Eta_1	0.688924	Eta_2	0.639698

maximum efficiency. Figure 9 demonstrates the total resistance and thrust of the initial and compromise solutions and also confirms that the resistance has been balanced by the propeller thrust at a wide range of Froude numbers, especially in design conditions, $Fn = 0.22$ and 0.27.

Conclusions

This paper concerns multidisciplinary optimization of a typical 14,000 TEU container ship, DTC, driven by the single propeller DTMB P4119, by using two different numerical methods with variable fidelity. This methodology is used to integrate the conceptual and preliminary stages of ship design and optimizes HPSs automatically in one stage.

The obtained results demonstrated the effectiveness and capability of the NSGA-II algorithm for finding the optimal solutions which were uniformly distributed over the Pareto front. Regarding the main dimensions of the optimized hulls, the length was increased and the breadth and draft were decreased which led to a significant reduction in wave-making and, hence, resistance compared to those of the initial hull. The increase in propeller diameter has a relatively stronger influence on the hydrodynamic performance than an increase in number of blades or decrease in pitch ratio which usually have negative effect on propeller performance. Shifting the advance coefficients to the location of maximum efficiency confirms an increase in the efficiency of the optimized propellers. The comparison between the initial and compromise solutions showed an improvement in the total hull resistance and propeller efficiency. The propeller thrust of the initial and compromise solutions satisfied the total hull resistances across a wide range of Froude numbers.

It is important to note that shortcomings are attributed to the inability of the solvers to capture the physics of the problem, especially 3D viscous flows and discretization of the bodies and free surface near the parts with severe curvature changes. All obtained results lead to a conclusion that the optimization strategy developed in the present study is efficient and worthy of further investigation and can aid practical ship design at early design stages.

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References

1. Benini, E. (2003) Multiobjective design optimization of B-screw series propellers using evolutionary algorithms. *Marine Technology* 40(4), pp. 229–238.
2. Burger, C. (2007) *Propeller performance analysis and multidisciplinary optimization using a genetic algorithm*. Dissertation, Auburn University, Alabama.
3. Day, A.H. & Doctors, L.J. (1997) Resistance optimization of displacement vessels on the basis of principal parameters. *Journal of ship research* 41(4), pp. 249–259.
4. Deb, K., Pratap, A., Agarwal, S. & Meyarivan, T. (2002) A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Transactions on Evolutionary Computation* 6(2), pp. 182–197.
5. Dejhalla, R., Mrša, Z. & Vuković, S. (2002) A genetic algorithm approach to the problem of minimum ship wave resistance. *Marine Technology* 39(3), pp. 187–195.
6. Gaafary, M., El-Kilani, H. & Moustafa, M. (2011) Optimum Design of B-Series Marine Propellers. *Alexandria Engineering Journal* 50(1), pp. 13–18.
7. Ghassemi, H. (2009) The effect of wake flow and skew angle on the ship propeller performance. *Scientia Iranica* 16(2), pp. 149–158.
8. Ghassemi, H. & Kohansal, A. (2010) Hydrodynamic analysis of non-planing and planing hulls by BEM. *Scientia Iranica. Transaction B: Mechanical Engineering* 17(1), pp. 41–52.
9. Ghassemi, H. & Zakerdoost, H. (2017) Ship hull–propeller system optimization based on the multi-objective evolutionary algorithm. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* 231 (1), pp. 175–192.
10. Ghose, J. & Gokarn, R. (2004) *Basic ship propulsion*. New Delhi: Allied Publishers.
11. Grigoropoulos, G.J. & Chalkias, D.S. (2010) Hull-form optimization in calm and rough water. *Computer-Aided Design* 42 (11), pp. 977–984.
12. Jeong, S. & Kim, H. (2013) Development of an efficient hull form design exploration framework. *Mathematical Problems in Engineering*, Article ID 838354, 12 pages.
13. Jiang, J., Cai, H., Ma, C., Qian, Z., Chen, K. & Wu, P. (2018) A ship propeller design methodology of multi-objective optimization considering fluid–structure interaction. *Engineering Applications of Computational Fluid Mechanics* 12 (1), pp. 1–13.
14. Kim, H.J., Choi, J.E. & Chun, H.H. (2016) Hull-form optimization using parametric modification functions and particle swarm optimization. *Journal of Marine Science and Technology* 21(1), pp. 129–144.
15. Mirjalili, S., Lewis, A. & Mirjalili, S.A.M. (2015) Multi-objective optimisation of marine propellers. *Procedia Computer Science* 51, pp. 2247–2256.
16. Park, J.H., Choi, J.E. & Chun, H.H. (2015) Hull-form optimization of KSUEZMAX to enhance resistance performance. *International Journal of Naval Architecture and Ocean Engineering* 7(1), pp. 100–114.

17. Pluciński, M.M., Young, Y.L. & Liu, Z. (2007) *Optimization of a self-twisting composite marine propeller using genetic algorithms*. 16th International Conference on Composite Materials ICCM-16, Kyoto, Japan.
18. Szelangiewicz, T., Wiśniewski, B. & Żelazny, K. (2014) Forecasting operating speed of the ship in the selected weather conditions. *Scientific Journals of the Maritime University of Szczecin, Zeszyty Naukowe Akademii Morskiej w Szczecinie* 38 (110), pp. 89–95.
19. Szelangiewicz, T. & Żelazny, K. (2015) An approximate method for calculating the mean statistical service speed of container ships on a given shipping line and its application in preliminary design. *Scientific Journals of the Maritime University of Szczecin, Zeszyty Naukowe Akademii Morskiej w Szczecinie* 44 (116), pp. 34–42.
20. Wikipedia (2018) List of largest container ships. [Online] Available from: https://en.wikipedia.org/wiki/List_of_largest_container_ships [Accessed: February 10, 2018]
21. Xie, G. (2011) Optimal preliminary propeller design based on multi-objective optimization approach. *Procedia Engineering* 16, pp. 278–283.
22. Zakerdoost, H., Ghassemi, H. & Ghiasi, M. (2013) Ship hull form optimization by evolutionary algorithm in order to diminish the drag. *Journal of Marine Science and Application* 12 (2), pp. 170–179.
23. Zhang, B.-j., Ma, K. & Ji, Z.-s. (2009) The optimization of the hull form with the minimum wave making resistance based on Rankine source method. *Journal of Hydrodynamics*, *Ser. B* 21 (2), pp. 277–284.