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MISSION-BASED HULL-FORM AND PROPELLER OPTIMIZATION OF A TRANSOM STERN DESTROYER FOR BEST PERFORMANCE IN THE SEA ENVIRONMENT

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Abstract. An overview is presented of the activities conducted within the NATO STO Task Group AVT-204 to "Assess the Ability to Optimize Hull Forms of Sea Vehicles for the Best Performance in a Sea Environment." The objective is the development of a greater understanding of the potential and limitations of the hydrodynamic optimization tools. These include low- and high-fidelity solvers, automatic shape modification methods, and multi-objective optimization algorithms, and are limited here to a deterministic application. The approach includes simulation-based design optimization methods from different research teams. Analysis tools include potential flow and Reynolds-averaged Navier-Stokes equation solvers. Design modification tools include global modification functions, control point based methods, and parametric modelling by hull sections and basic curves. Optimization algorithms include particle swarm optimization, sequential quadratic programming, genetic and evolutionary algorithms. The application is the hull-form and propeller optimization of the DTMB 5415 model for significant conditions, based on actual missions at sea.

1 INTRODUCTION

In order to reduce costs and improve the performance for a variety of missions, navies are demanding new concepts and multi-criteria optimized ships. In order to address this challenge, research teams have developed simulation-based design optimization (SBDO) methods, to generate hull variants and optimize their hydrodynamic performance, combining low- and high-fidelity solvers, design modification tools, and single/multi-objective optimization algorithms. The NATO RTO Task Group AVT-204, formed to "Assess the Ability to Optimize Hull Forms of Sea Vehicles for Best Performance in a Sea Environment," [1] addressed the integration and assessment of different computational methods and SBDO approaches, bringing together teams from France (ECN-CNRS, Ecole Centrale de Nantes), Germany (TUHH, Hamburg University of Technology), Greece (NTUA, National Technical University of Athens), Italy (CNR-INSEAN, National Research Council-Marine Technology Research Institute), Turkey (ITU, Istanbul Technical University), and Unites States (UI, University of Iowa).

The objective is the development of a greater understanding of the potential and limitations of the hydrodynamic optimization tools and their integration within SBDO. The former include automatic shape modification tools, low- and high-fidelity solvers, and multi-objective optimization algorithms, and are limited in the present activity to deterministic applications.

The approach encompasses SBDO methods from different research teams, which are assessed and compared. INSEAN and UI undertook a joint effort for a two phase SBDO, using low-fidelity solvers in the first phase, and more accurate and computationally expensive high-fidelity solvers in the second phase. ITU and NTUA performed separate SBDO procedures, based on low-fidelity solvers, whereas ECN-CNRS used a high-fidelity solver to verify low-fidelity optimization outcomes. TUHH addressed the propulsion optimization for the unsteady wake field produced by the optimized hull form. SBDO tools and results are presented in the following, for each research team separately. Analysis tools used in the current study include potential flow (INSEAN/UI, ITU, NTUA, TUHH) and RANS (ECN-CNRS, INSEAN/UI) solvers. Design modification tools include linear expansion of orthogonal basis functions (INSEAN/UI), an approach based on relaxation coefficients at control points with Akima's surface generation (ITU), and the parametric modelling of the CAESES/FRIENDSHIP-Framework, using a set of basic curves, with associated topological information (NTUA). Multi-objective optimization algorithms include a multi-objective extension of the deterministic particle swarm optimization (INSEAN/UI), a sequential quadratic programming method, which is applied to an artificial neural network model of aggregate objective functions (ITU), and a non-dominated sorting genetic algorithm (NTUA). TUHH modifies the propeller design parameters using a genetic algorithm from Sandia's Dakota tool kit. The methods and implementations of the optimization procedures were also presented in [1, 2].

The test case for the current study is a deterministic hull-form and propeller optimization of a USS Arleigh Burke-class destroyer, namely the DDG-51 (Fig. 1). The DTMB 5415 model, an open-to-public early concept of the DDG-51, is used for the current research. This has been largely investigated through towing tank experiments [3], and used for earlier SBDO research for conventional/hybrid hulls [4]. Both 5415 bare hull (INSEAN/UI, ECN-CNRS) and the 5415M variant with skeg only (ITU, NTUA) are addressed. The design optimization exercise aims at the reduction of two objective functions, namely (i) the weighted sum of the total resistance in calm water at 18 and 30 kn (corresponding to Fr=0.25 and 0.41), and (ii) a seakeeping merit factor based on the vertical acceleration at the bridge (in head wave, sea state 5, Fr=0.41) and the roll motion (in stern wave, sea state 5, Fr=0.25). The first speed for resistance optimization (18 kn) is close to the peak of the speed-time profile for transits, from 2013 data [5]. The second speed (30 kn) is the flank speed, used as an objective to minimize the maximum powering requirements. The seakeeping merit factor is based on a first quite extreme condition, and on a second less extreme condition. Sea state 5 is considered, as a commonly encountered open ocean condition for North Atlantic and North Pacific, year round [6]. Although deterministic, the present conditions are a reasonable representation of the operations of a DDG-51.

An early version of this paper was presented in [2], focusing on the low-fidelity hull-form optimization and preliminary validation with RANS. These are extended here, where a complete validation by RANS is presented, along with the propeller optimization and a final RANS-based hull-form optimization.

2 HULL-FORM OPTIMIZATION PROBLEM

The main particulars of the full scale model and test conditions are summarized in Tab. 1. The optimization aims at improving both calm-water and seakeeping performances, and is formulated as

$$\begin{array}{lll} \text{Minimize} & \{f_1(\mathbf{x}), f_2(\mathbf{x})\}^T & \\ \text{subject to} & g_k(\mathbf{x}) = 0, & k = 1, \ldots, K \\ \text{and to} & h_l(\mathbf{x}) \leq 0, & l = 1, \ldots, L \end{array} \tag{1}$$

where $\mathbf{x}$ is the design variable vector, the first objective f_1 is the weighted sum of the normalized total resistance in calm water at 18 kn (Fr=0.25) and 30 kn (Fr=0.41), respectively,

$$f_1(\mathbf{x}) = 0.85 \left. \frac{R_T}{R_{T_0}} \right|^{18\text{kn}} + 0.15 \left. \frac{R_T}{R_{T_0}} \right|^{30\text{kn}} \tag{2}$$

with R_{T_0} the total resistance of the parent hull. This formulation is based on the expertise of the members and some statistical data from US Navy, that destroyers operate most of their time at the fleet speed (close to 18 kn) and only 15% at the maximum speed (around 30 kn). The second objective f_2 is a seakeeping merit factor, defined as

$$f(\mathbf{x}) = 0.5 \left. \frac{RMS(a_z)}{RMS(a_{z_0})} \right|_{180\text{deg}}^{30\text{kn}} + 0.5 \left. \frac{RMS(\varphi)}{RMS(\varphi_0)} \right|_{30\text{deg}}^{18\text{kn}} \tag{3}$$

where RMS represents the root mean square, a_z is the vertical acceleration at the bridge (located 27 m forward amidiships and 24.75 m above keel) at 30 kn in head long-crested waves (180 deg), and φ is the roll angle at 18 kn in stern long-crested waves (30 deg). The wave conditions corresponds to sea state 5, using the Bretschneider spectrum with a significant wave height of 3.25 m and modal period of 9.7 s. Subscript '0' refers to parent-hull values.

The selected dynamic responses are critical at completely different operating conditions (speed, heading, location along the vessel). However, we assume that similar sea conditions prevail in both cases, which form the seakeeping objective. The contribution of each operating condition in the objective is the same (50%).

Geometrical equality constraints, $g_k(\mathbf{x})$, include fixed length between perpendicular and displacement, whereas geometrical inequality constraints, $h_l(\mathbf{x})$, include limited variation of beam and draught, ±5%, and reserved volume for the sonar in the dome, corresponding to 4.9 m diameter and 1.7 m length (cylinder).

Table 1: DTMB 5415 model main particulars (full scale)

Description	**Symbol**	**Unit**	**Value**
Displacement	∇	tonnes	8,636
Lenght between perpendiculars	LBP	m	142.0
Beam	B	m	18.90
Draft	T	m	6.160
Longitudinal center of gravity	LCG	m	71.60
Vertical center of gravity	VCG	m	1.390
Roll radius of gyration	K_{xx}	–	$0.40B$
Pitch radius of gyration	K_{yy}	–	$0.25LBP$
Yaw radius of gyration	K_{zz}	–	$0.25LBP$
Speed	U	kn	{18;30}
Froude number	Fr	–	{0.25;0.41}
Water density	ρ	kg/m^3	998.5
Kinematic viscosity	ν	m^2/s	$1.09 \cdot 10^{-6}$
Gravity acceleration	g	m/s^2	9.803

Figure 1: USS Arleigh Burke Bravo Sea Trials Gulf Off Maine (U.S. Navy photo)

3 HULL-FORM OPTIMIZATION PROCEDURES AND RESULTS

Three partners, INSEAN/UI, ITU and NTUA undertook independently the optimization task, while ECN-CNRS was responsible for the evaluation of the three derived optimized hull forms and the selection of the most promising one. INSEAN/UI carried out additional CFD calculations, whereas TUHH performed the assessment and optimization of the propeller for the optimal hull form. The following subsection presents briefly the main details of the procedures and the results obtained by INSEAN/UI, ITU, and NTUA, whereas the RANS verification, propeller optimization and additional hull form optimization based on RANS are presented in sections 4, 5, and 6, respectively. Further details may be found in [1, 2].

3.1 INSEAN/UI

The SBDO framework used for the first optimization phase by INSEAN/UI integrates low-fidelity solvers of calm-water resistance and seakeeping prediction, a design modification method based on linear expansion of orthogonal basis function [7], and single/multi-objective optimization algorithm based on the particle swarm metaheuristic [8, 9]. The WAve Resistance Program (WARP), a linear potential flow code (in-house developed at INSEAN) is used for the calm-water prediction. Details of equations, numerical implementations, and validation of the numerical solver are given in [10]. The Standard Ship Motion program (SMP), developed at the David Taylor Naval Ship Research and Development Center, a potential flow solver based on linearized strip theory, is used for the seakeeping prediction [11].

The comparison of WARP and SMP with EFD data for the original DTMB 5415 have shown a reasonable agreement. Grid studies have been also performed. Six design spaces are investigated varying the space dimension (with dimensionality ranging from two to six) and the associated design variables bounds. The design space is defined using orthogonal modification functions.

Sensitivity analysis are performed for resistance and motions, showing a significant variability of the performance. The same design spaces are used for single-objective optimization for separate f_1 and f_2, achieving an improvement by nearly 12% and 13.3% respectively. Multi-objective optimization combining f_1 and f_2 is finally performed. The most promising design produces an improvement of nearly 7% for both, f_1 and f_2 and is selected for further investigation by RANS.

3.2 ITU

ITU uses a relatively simpler approach in obtaining design modifications (experimental space). The hull form variation is based on a limited number of control points, laying on specific (two in the demo case) waterlines and stations (six in the demo case) along the hull. On these control points relaxation coefficients 1 ± 0.05 are applied to deform the hull form and to generate variants. Each variant is then faired using Akima's method [12]. On the basis of the generated data base of 250 modified hull forms a static Artificial Neural Network (ANN) is trained and the combined (or aggregate) objective function is expressed as $F^W_{Combined} = wf_1 + (1-w)f_2$ where $w = \{0, 0.1, \ldots, 0.9, 1.0\}$ is employed as a weighting factor. The selected optimization algorithm is based on sequential quadratic programming (SQP) within Matlab optimization toolbox, suitable for constraint optimization problems whose design variables include upper and lower bounds. The optimal forms for each weighting factor w are investigated by considering $F^W_{Combined}$ in the ANN training process. The SQP application on the metamodel provided by the ANN gives an optimal point, which is expected to be part of the overall Pareto front. Using the above methodology and numerical analysis by low-fidelity solvers (ITU-Dawson and ITU-SHIPMO for calm-water and seekeeping, respectively) point out 7% and 13.5% improvements in resistance and seakeeping performances, respectively, attained by the selected optimal hull.

3.3 NTUA

The optimization is based on the parametric representation of the hull form using CAESES/ FRIENDSHIP-Framework. The design is split into a set of surfaces and a total number of ten design variables were selected for hull variation. Five of them refer to the main hull and the rest to the sonar dome. For the hydrodynamic evaluation of the parent and the variant hull forms SWAN2 and SPP-86 potential flow codes are used. The multi-objective optimization with respect to Eq. 1 is carried out by employing the Non-dominating Sorting Genetic Algorithm-II (NSGA-II, [13]). Parametric modeling using B- and F-Splines, variation and optimization is integrated in CAESES/FFW environment. The hydrodynamic evaluation of the variant hull forms was carried out via the aforementioned codes called within the same environment. The methodology after the generation and the evaluation of 400 faired variants concludes with a Pareto front offering optimized hull forms with varying improvements in resistance and seakeeping. In this case, the improvement in the former results in deterioration of the latter. The selected optimized hull form constitutes a compromise over the two selection criteria, which takes into consideration the magnitude of the improvement in each criterion and its significance on the overall performance of the vessel. The finally proposed optimum hull form offers resistance index reduced by 17% and seakeeping index reduced by 6% over the parent one.

4 VALIDATION OF OPTIMIZED HULL FORMS USING HIGH-FIDELITY SIMULATIONS

The objective of the work by ECN-CNRS is to validate the optimized geometries (full scale) with their in-house ISIS-CFD code [14, 15, 16]. The flow solver, available as a part of the FINE^{TM}/Marine computing suite, is an incompressible unsteady Reynolds-averaged Navier-Stokes (URANS) method mainly devoted to marine hydrodynamics (a typical domain is shown in Fig. 2).

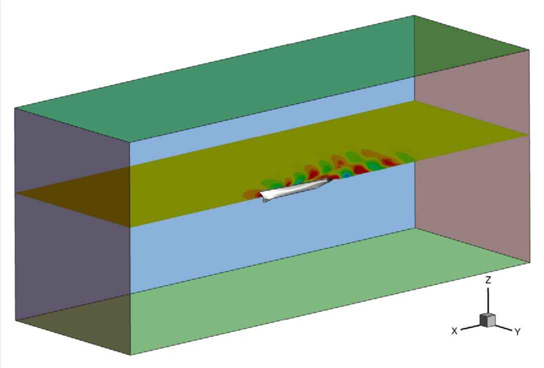
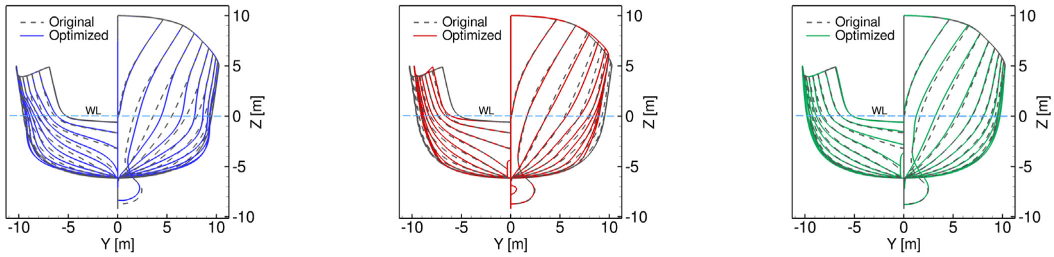


Figure 2: ISIS-CFD computational domain and boundaries with a computed free surface

ECN-CNRS evaluated two designs proposed by INSEAN, the NK-WC (obtained by Neumann-Kelvin linearization with the transverse Wave Cut method [17]) and DM-PI (obtained by Double-Model [18] Pressure Integral method), and the designs proposed by ITU and NTUA (Fig. 3). The latest was found significantly better than the other three with respect to the present rating criteria. Furthermore, the calm water resistance reduction of the optimized over the parent hull form as predicted by SWAN2 2002 software, a potential flow method incorporated in NTUAs methodology, is quite similar to the one derived using the URANS method. The other three potential flow methods overestimate the performance improvement of the optimized hull. The NTUA geometry offers a 6.1% reduction for f_1, and specifically a 8.8% reduction of total resistance at Fr=0.25, with a 3% increment at Fr=0.41.

Table 2: Optimization results summary: RANS validation of PF-based optimal solutions

Geometry	$C_T \times 10^{-3}$ [–] Fr = 0.25	$C_T \times 10^{-3}$ [–] Fr = 0.41	$\Delta f_1\%$	RMS(a_z) [m/s^2] 180deg	RMS(ϕ) [rad] 30deg	$\Delta f_2\%$
Original	2.702	4.960	–	1.296	0.018	–
INSEAN/UI	3.018	5.314	9.3	1.254	0.020	3.1
NTUA	2.435	5.112	-6.1	1.314	0.019	0.7
ITU	2.801	5.043	6.2	1.275	0.019	1.2

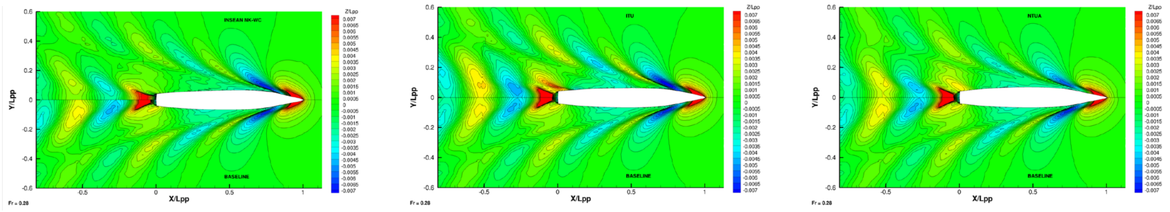


(a) INSEAN/UI (NK-WC) (b) ITU (c) NTUA

Figure 3: Optimized and original hull stations

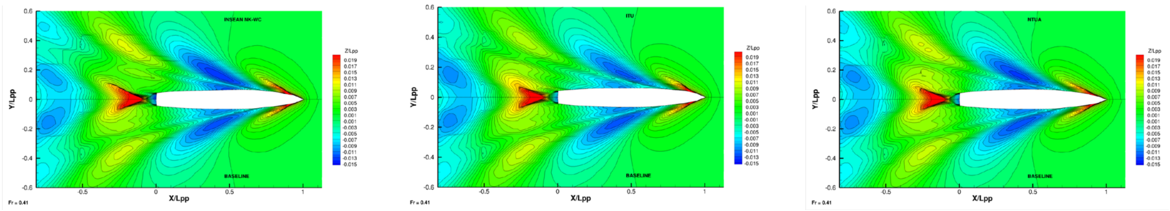
The seakeeping calculations using URANS code were limited and the achieved changes on the vertical dynamic responses were quite limited.

Figures 4 and 5 show the wave elevation patterns evaluated by ISIS-CFD at Fr=0.28 (used for comparison with experimental data available for the original hull) and Fr=0.41, respectively. A summary of the results is presented in Tab. 2.



(a) INSEAN/UI (NK-WC) (b) ITU (c) NTUA

Figure 4: Optimized and original wave elevations distribution for calm water at Fr=0.28



(a) INSEAN/UI (NK-WC) (b) ITU (c) NTUA

Figure 5: Optimized and original wave elevations distribution for calm water at Fr=0.41

5 PROPELLER OPTIMIZATION FOR OPTIMIZED HULL FORM

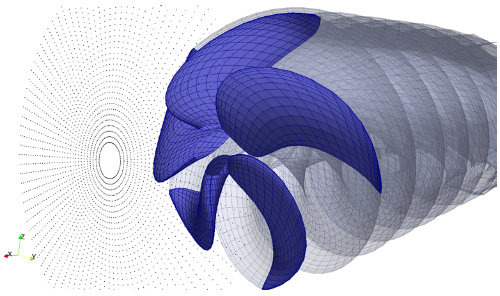


Figure 6: *pan*MARE computational grid

TUHH team used the in-house boundary element solver *pan*MARE (a typical grid is shown in Fig. 6) and the wake field provided by ECN-CNRS CFD-code ISIS to design the propeller. The latter always works in an inhomogeneous wake field due to the presence of the ship's hull in front of the propeller. This wake field is a major design factor for the propeller. Although the propeller is usually designed on the basis of the calm water condition, it has to cope with the real operation conditions where the wake field is unsteady due to the incoming waves and the ship motions. The unsteady wake field can be a reason for increasing the power demand and the pressure fluctuation amplitudes. Within this study advanced optimization algorithms are used to design propellers with improved characteristics in seaways. The varying wake field is considered at four cases within a cycle of a regular wave, propeller on the crest or the trough and at a wave node moving up- or downwards.

The variant propeller designs were evaluated in two stages. The aim of the first stage is to develop geometries, which satisfy the demand for averaged delivered thrust with a minimum value of required torque. In a second stage, a number of most successful designs are investigated regarding their cavitation behavior.

The goal of this study is to design an optimal propeller for an unsteady operating conditions. After a number of simplifications, a numerical setup is achieved that allows for considering the most important physical aspects of the problem. The setup is used to evaluate the individuals generated within a defined search space. The number of individuals which satisfy the imposed constraint is gradually increased with the evolutionary progress of the optimization. In addition, the propeller efficiency also shows a considerable improvement. The shape of the optimized propeller and the pressure distribution are shown in Fig. 7. The analysis of the optimized geometries shows that the pitch is reduced at the tip to limit the tip vortex circulation. Accordingly, a slight increase in camber is present. For mid-section parameters, a slow convergence behavior has been observed. The influence of the evolutionary algorithm settings on the results should therefore be studied with regard to accelerating the convergence while retaining the converging character. In a second simulation stage, the best individuals from the evolutionary run are evaluated concerning cavitation probability. Many geometries show little thin cavitating line near the leading edge in the investigated operating conditions. Further numerical studies based on RANS-simulations are needed to check whether phenomena like leading edge vortex may be the reason for local separation in this area. Details may be found in [1].

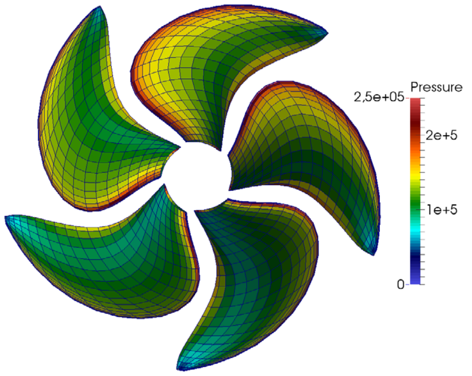
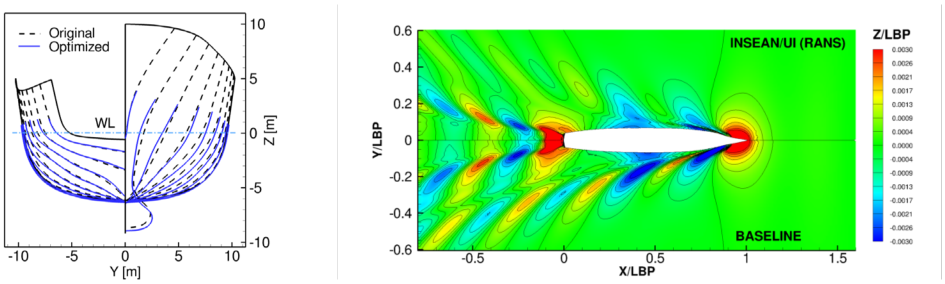


Figure 7: Shape and pressure distribution on the optimal propeller

6 EFFECTS OF LOW- AND HIGH-FIDELITY SOLVERS ON HULL-FORM OPTIMIZATION

High-fidelity solvers (such as RANS) have shown their capability to provide accurate solutions to the design problem [19]. Their computational cost is still a critical issue in SBDO. For this reason, metamodels and variable-fidelity approaches, based on low- and high-fidelity solvers, have been developed and applied to reduce the computational time and cost of the SBDO. Low-fidelity solvers (such as potential flow, PF) have been applied to identify suitable design spaces for RANS-based optimization. Identifying the proper trend of the design objective versus the design variables often represents a critical issue for a low-fidelity solver, especially when large design modifications are involved. The choice of a low-fidelity solver within SBDO represents a critical issue and should be carefully justified, considering the trade-off between computational efficiency and solution accuracy.

INSEAN/UI compared the effects of four PF formulations and implementations on the results of the multi-objective SBDO problem in Eq. 1. Kelvin and Dawson linearization (referred to as Neumann-Kelvin, NK, and double model, DM, respectively) are used with a standard pressure integral over the body surface (referred to as PI) and the transverse wave cut method (referred to as WC), for the wave resistance calculation. A sensitivity analysis at Fr=0.25 using RANS is shown in [1], for comparison and correlation with the potential flow solutions. The code WARP was used as PF solver, whereas the RANS computations were performed with the code CFDShip-Iowa [20, 21]. It was found that the PF formulation significantly affects the SBDO outcomes. Specifically, the Pareto fronts look quite different and the selected optimal designs fall in different region of the design space, depending on the PF formulation used. The following considerations can be made [1]: the validation for the original hull shows reasonable trends, but NK-PI for low Fr; DM shows better validation especially for sinkage, compared to NK; NK-PI provides significant resistance reductions at low Fr (likely due to an overestimate of the resistance for the original hull) and more limited improvements at high Fr; NK-WC shows a quite opposite trend; DM-PI indicates more limited (and realistic) improvements, for both low and high Fr; it also shows a limited possibility of improving both objectives at the same time; DM-WC provides more significant resistance reduction at high Fr; overall, the WC method always indicates greater improvements at high Fr than PI, likely due to an overestimate for the resistance of the original hull; NK results seem more affected by the wave resistance estimation method than DM.



(a) Hull stations (b) Wave elevation pattern

Figure 8: Comparison of optimized and original hull stations and wave elevation distribution at Fr=0.25

These outcomes motivated further investigations by RANS. Specifically, a sensitivity analysis at Fr=0.25 was conducted and compared with the PF results, showing several differences between PF and RANS solutions. Specifically, none of the PF formulations showed a reasonable trend for all the design variables, compared to RANS. The analysis of the Pearsons correlation coefficient between PF and RANS results showed a good correlation between NK-PI and RANS for four out of six variables. For the current application, NK-PI is the more effective PF formulation.

Table 3: Comparison between original and INSEAN/UI RANS-optimized DTMB 5415 hydrodynamic coefficients

Parameter	Unit	Original	Optimized	Δ%
C_{pp}	–	1.38E-03	9.08E-04	-34.0
C_h	–	0.86E-03	1.24E-03	42.0
C_f	–	3.16E-03	3.18E-03	0.65
$C_{mg,x}$	–	-1.19E-03	-1.35E-03	-13.4
C_T	–	4.21E-03	3.97E-03	-6.00
σ/LBP	–	-1.31E-03	-1.35E-03	-3.29
τ	deg	-0.11	-0.12	-15.3
$S_{w,stat}/LBP^2$	–	1.48E-02	1.50E-02	0.96

Since low-fidelity solvers can lead to inaccurate design solutions (especially for large design modifications and possible flow separation), a further RANS-based optimization of the DTMB 5415 bare hull was proposed. Specifically, a deterministic derivative-free single-objective optimization was performed, using global/local hybridization by derivative-free line search methods of two well-known global algorithms, DIRECT and DPSO, respectively [1, 7]. The optimization aimed at the reduction of the (model scale) total resistance coefficient in calm water at Fr=0.25. The design space was generated by a linear expansion of orthogonal basis functions for the modification of the hull form. The problem was solved with a number of design variables equal to eleven. A resistance reduction of 6% was achieved by the optimized design. The final shape obtained with RANS induces a high pressure region in correspondence of the first trough of the diverging bow wave of the original hull. This causes a phase shift with a significant reduction of the bow wave and the cancellation of the shoulder wave. As a result, the pressure distribution appears more uniformly distributed along the hull and most of the resistance reduction stems from the piezometric pressure coefficient. The final hydrodynamic assessment of the RANS-based optimized shape has confirmed the effectiveness of the SBDO procedure, driven by hybrid global/local methods. Results are shown in Tab. 3 and Fig. 8.

7 CONCLUSIONS

A multi-objective hull form and propeller optimization of the DTMB 5415 (specifically the MARIN variant 5415M, with skeg only) was investigated using low- and high-fidelity solvers, performed by different research team (INSEAN/UI, ITU, NTUA, ECN-CNRS, and TUHH). Overall, optimization achievements by low-fidelity solvers were found significant, with an average improvement for calm-water resistance and seakeeping performances of 10 and 9% respectively. The most promising designs show up to 16% improvement for the calm-water resistance and 14% for the seakeeping merit factor. The design-space size ranged from two to twelve and the optimized designs show a quite large variability and different characteristic.

INSEAN/UI defined six design spaces with dimensionality ranging from two to six, using a linear expansion of orthogonal basis functions for the modification of the DTMB 5415 bare hull. The optimization was performed by a multi-objective extension of the deterministic particle swarm optimization algorithm. ITU produced 250 hull form variants of the 5415M using Akima's surface generation, with randomly distributed relaxation coefficients at control points over the body surface. The optimization procedure combined an artificial neural network with a sequential quadratic programming algorithm, which is fed with aggregate objective functions. NTUA used the parametric modelling of the CAESES/FRIENDSHIP-Framework for the design modification of the 5415M, representing the hull form by a set of basic curves, providing topological information, and defining a set of 19 sections. The hull surface was parametrized by ten design variables. The NSGA II code was used for the optimization procedure. ECN-CNRS verified parent and optimal hulls, using an in-house high-fidelity solver (ISIS-CFD). The geometry provided by NTUA was selected as the best candidate, providing a 6.1% reduction of the calm water resistance (weighted average at Fr=0.25 and 0.41). TUHH performed the propeller optimization considering the unsteady wake field in waves. Finally, further investigations on the effects of potential flow formulation/linearization on the multi-objective optimization were proposed by INSEAN/UI, along with a RANS-based optimization.

The methodologies proposed have been found a viable option for SBDO. Low-fidelity solvers have shown some limitations in the prediction of the objective trends (especially for the resistance). High-fidelity solvers should be used, whenever possible. SBDO techniques are mature for extension to more complex aspects of the hydrodynamics of naval combatants (maneuvering, intact and dynamic stability, etc.) as well as other items/disciplines (structures, operations, economic management, weight, etc.). Moving to more complex, real-world, multi-disciplinary problems [22], particular attention should be paid to the trade-off between computational accuracy and cost, and the interplay among the different elements and disciplines involved. Finally, SBDO research would benefit from experimental fluid dynamics (EFD) of original and optimized designs, whenever possible.

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