

Hydrofoil Installation and Performance Optimisation for Ship Resistance Reduction in Trimaran Through Particle Swarm Optimisation Method

Aliakbar Ghadimi ¹

Parviz Ghadimi ¹ * 

Hassan Ghassemi ^{1,2} 

¹ Dept. of Maritime Engineering, Amirkabir University of Technology, Iran

² School of Ocean Engineering, Harbin Institute of Technology, Weihai, China

* Corresponding author: pghadimi@aut.ac.ir (Parviz Ghadimi)

ABSTRACT

The trimaran vessel performs well both in calm waters and in waves. To improve its hydrodynamic efficiency, a hydrofoil is installed at the rear part of the trimaran. The primary aim of this hydrofoil is to reduce the overall resistance while the ship is moving. This study focuses on minimising the ship's total resistance. An optimisation process is designed to determine the best position and angle of attack (AoA) for the hydrofoil at the design speed. To achieve this, a multi-disciplinary optimisation (MDO) platform is employed to conduct a computation fluid dynamics (CFD)-based automated design study. The optimisation method integrates STAR-CCM+ software with the particle swarm optimisation (PSO) algorithm as the optimiser. The flow field and wave patterns around the trimaran are analysed to assess resistance improvements. The results reveal that the optimal position for the NACA6612 hydrofoil is towards the stern and away from the midship, with the ideal AoA being 5.19 degrees at cruising speed. Comparisons indicate that the resistance of the trimaran with the optimised hydrofoil is reduced by approximately 4.49% compared to a trimaran without the hydrofoil.

Keywords: trimaran, hydrofoil, hydrodynamics, resistance, optimisation

INTRODUCTION

In recent years, trimarans have become increasingly practical for a range of operational scenarios. They offer high-speed performance, excellent stability, and generous space for various layouts. Hydrofoil sections are frequently used and preferred for lifting surfaces, serving as additional appendages on the ship's hull.

The use of hydrofoils in trimaran vessels has been studied to enhance performance by reducing resistance, improving speed, and increasing hydrodynamic efficiency. Various hydrodynamic optimisation techniques have been applied to investigate how different factors, such as the hull design and hydrofoil integration, affect the vessel's

resistance. Numerical and experimental studies show that hull shape optimisation, including hydrofoil applications, significantly reduces resistance [1-3]. Studies, such as that of Yıldız [4], have investigated the residual resistance of trimarans using an artificial neural network (ANN), highlighting how positioning hulls and optimising design features like hydrofoils can drastically cut down on residual resistance. This study demonstrated how an ANN can predict optimal locations for hydrofoils to reduce resistance. Wang [5] conducted an experimental study on the impact of hydrofoils and other features such as spray rails and stern flaps in reducing the resistance of trimaran planing hulls. Hydrofoils, when incorporated properly, were proven to lower drag and contribute to enhanced fuel efficiency at high

speeds. On the other hand, Ma et al. [6] conducted model tests on trimaran vessels with and without hydrofoils. Their study found that hydrofoils significantly improved resistance characteristics by reducing the hull's wave-making effect and enhancing aerodynamic lift. Hydrofoils, in conjunction with stepped hulls, demonstrated superior performance in high-speed conditions, reducing resistance peaks and improving seakeeping abilities. Korepanov and Ronnov [7] investigated how the geometric characteristics of central hulls and outriggers affect trimaran resistance during the early stages of design. Although hydrofoils were not directly studied, the experimental methods outlined in this paper could easily be adapted to include hydrofoil testing. Their findings on optimising outrigger placement are essential for further research on hydrofoil integration.

Generally, industrial applications of hydrofoils involve placing them around the floating body to minimise resistance. Specifically, multi-hull vessels equipped with hydrofoils inside their structures avoid issues related to mooring and interactions with other structures. In this article, a hydrofoil is installed at the rear of a trimaran ship. Hydrofoils are particularly effective for lightweight vessels due to their ability to generate both lift and momentum, which helps reduce running trim, sinkage, and resistance. The main aim of this paper is to propose an automated solution for determining the optimal position and angle of attack (AoA) for the hydrofoil on a trimaran vessel. This solution seeks to maximise hydrofoil performance through the use of advanced software tools and optimisation algorithms. Significant research has been conducted on reducing resistance in trimarans. Nazemian and Ghadimi [8] explored how the outrigger configuration affects the resistance of a trimaran hull and extended their research to seakeeping and multi-design speed performance [9,10]. Their findings suggested that positioning the side hulls slightly aft of the main hull's stern and increasing the transversal distance improved performance in both calm and wavy conditions. Verna et al. [11] performed an optimisation analysis of the trimaran hull setup to determine the ideal stagger and distance between the side hulls. Deng et al. [12] used computational fluid dynamics (CFD) simulations to assess trimaran resistance with appendages under both free and constrained conditions, considering six degrees of freedom. Their study found a strong correlation between the numerical results and experimental data. Zhang et al. [13] employed a combined approach to evaluate trimaran resistance and waterjet propulsion efficiency, discovering that positioning the secondary hull at the aft of the primary hull significantly enhanced the propulsion performance. Wang et al. [14] examined the seakeeping performance of a self-navigating catamaran equipped with hydrofoils in regular waves, showing a reduction in the vessel's motion compared to its initial state. This paper calculates the longitudinal and vertical positioning of a NACA 6612 hydrofoil in order to achieve minimal resistance and identify the optimal AoA for efficient positioning. An efficient optimisation platform is proposed, integrating CAD (Computer Aided Design), CFD solvers, and optimisation algorithms [15]. This automated

process facilitates a comprehensive exploration of design options to achieve targeted performance levels. Recent developments in marine optimisation platforms include Guo et al.'s [16] study of a waterjet-propelled trimaran using a surrogate model and direct particle swarm optimisation (PSO) algorithm. They simulated the interaction between the propulsion system and trimaran hull.

Chen et al. [17] investigated various optimisation techniques for improving ship hull designs. These techniques included meta-models from stochastic mathematics and the PSO algorithm from heuristic optimisation methods. The use of surrogate models, or meta-models, helps reduce the computational effort and avoids the need for the direct simulation of each generated design. Nazemian and Ghadimi [18] focused on optimising the hull shape of a trimaran with a wave-piercing bow, addressing a multi-objective problem that considered both seakeeping and resistance. Their optimisation approach achieved a 3.14% reduction in the combined objective function, demonstrating the effectiveness of their proposed platform. Kaklis et al. [19,20] conducted extensive research on marine applications, employing various shape optimisation methods. Their work included advanced computational techniques and design analysis approaches like dimensionality reduction. Tahara et al. [21] examined the hull of a catamaran, applying both single and multi-objective optimisation strategies. They used free-form deformation (FFD) parametrisation to improve the catamaran's seakeeping and resistance performance.

The literature review indicates that there is currently no automated optimisation platform for hydrofoil installation on ship designs, especially for high-speed displacement trimarans. To address this gap, the total resistance of a hydrofoil-equipped trimaran at cruising speed is assessed using numerical simulations with the commercial software STAR-CCM+. The simulations employ the Reynolds-averaged Navier-Stokes (RANS) equations combined with the volume of fluid (VOF) method. Once the parameters are configured for variation within STAR-CCM+'s CAD environment, the PSO optimiser manages all automated optimisation processes. The hydrofoil's AoA is varied between 1 and 10 degrees. The optimal positioning of the NACA6612 hydrofoil and its impact on the trimaran's performance in calm water are determined, and the effects of the hydrofoil are analysed. Finally, the performance of the optimised trimaran with the hydrofoil is compared to that of a trimaran without the hydrofoil in terms of total resistance.

Hydrofoil optimisation goes far beyond the traditional hull optimisation studies of trimarans by introducing a new dimension of hydrodynamic efficiency, speed, and operational flexibility. While previous hull studies focused on passive improvements to the hull shape, hydrofoils allow dynamic, real-time adjustments to performance, providing superior drag reduction, enhanced fuel efficiency, and improved seakeeping. As the next frontier in trimaran design, hydrofoil optimisation represents a significant leap forward in maritime engineering.

PROBLEM DEFINITION

An analysis is conducted on a wave-piercing bow trimaran. The key features of the model are detailed in [22–24], and the 3D perspective view of the hull is shown in Fig. 1. The side hulls are designed in the Wigley form; they are known for their high efficiency in reducing resistance. These side hulls are located at the rear of the main hull's transom.

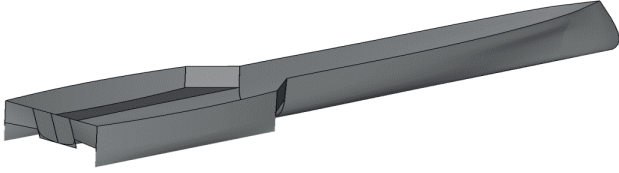


Fig. 1. Three-dimensional representation of the trimaran under consideration

Tab. 1. Key dimensions of the trimaran vessels [22–24]

Specifications	Main vessel	Scaled model
Total length (m)	124	3.1
Draft length (m)	123.2	3.08
Total width (m)	22.2	0.555
Central hull width (m)	5	0.125
Side hull length (m)	36	0.9
Draft (m)	4.384	0.1096
Clearance (side hull transverse distance)	9.7	0.2425
Stagger (side hull longitudinal distance)	0	0
Displacement	2248.8 (tonnes)	35 (kg)

Selecting and designing the suitable foils for ship appendages is a complex task that takes into account several factors, such as the hull shape, the location of the centre of gravity, and the interaction between the hull and the hydrofoils. Fig. 2 illustrates the trimaran ship with a hydrofoil installed at the rear; it can rotate between 1 and 10 degrees. The hydrofoil can move both vertically and longitudinally. The NACA6612 hydrofoil is depicted in Fig. 2 at both an angle of zero and the maximum AoA.

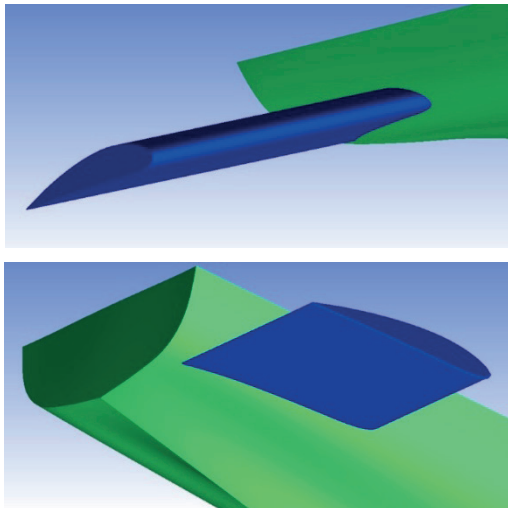


Fig. 2. Hull geometry with hydrofoil

OPTIMISATION FORMULATION

This paper focuses on optimising the hydrofoil trimaran to reduce resistance, with the primary objective being to minimise resistance at cruising speed. The problem of optimising the hull form in this context can be outlined as follows:

$$\begin{aligned} &\text{minimize } f_1(X) \\ &\text{subject to } X \in S \subseteq \mathbb{R}^N. \end{aligned} \quad (1)$$

In this study, f represents the objective function, which is the total resistance at cruising speed. The set $S \subseteq \mathbb{R}^N$ denotes the set of feasible solutions, with the feasible design space constrained by specific limits. The design variables X , which are in d dimensions, correspond to the parameters related to the hydrofoil's longitudinal and vertical positions, as well as its AoA [25]. The design variables and their respective ranges are outlined in Table 2.

Tab. 2. A list of design parameters

No.	Parameter	Characteristics	min. ≤ main ≤ max.
1	Dx	x-direction movement	−0.1 ≤ 0 ≤ +0.1
2	Dz	y-direction movement	−0.02 ≤ 0 ≤ +0.01
3	AoA	Angle of attack	1 ≤ 5 ≤ 10 deg

NUMERICAL FORMULATION

To simulate the flow domain around the hydrofoil, the finite volume method (FVM) is employed using Star CCM+ software, and the VOF method is applied to precisely capture the free surface [26]. For incompressible flow, in the absence of body forces, the RANS equations are formulated in Cartesian coordinates as follows:

$$\frac{\partial(\rho \bar{u}_i)}{\partial x_i} = 0, \quad (2)$$

$$\frac{\partial(\rho \bar{u}_i)}{\partial t} + \frac{\partial}{\partial x_j} (\rho \bar{u}_i \bar{u}_j + \overline{\rho u'_i u'_j}) = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial \bar{\tau}_{ij}}{\partial x_j}, \quad (3)$$

where $\bar{\tau}_{ij}$, the average viscous stress tensor, is given by

$$\bar{\tau}_{ij} = \mu \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right). \quad (4)$$

In this context, ρ represents the fluid density, $\bar{u}_i$ denotes the averaged Cartesian components of the velocity vector, $\bar{p}$ stands for the mean pressure, $\overline{\rho u'_i u'_j}$ indicates the Reynolds stresses, and μ is the dynamic viscosity. The solver uses a predictor-corrector method to link the momentum equations with the continuity equation. For turbulence modelling, the standard

k-ε model is employed; it is commonly used across various applications [27,28].

In the VOF scheme, the distribution of phases and α_i (interface position) is described by the fraction of phase i within the entire volume:

$$\alpha_i = \frac{V_i}{V}. \quad (5)$$

Here, V denotes the volume of the cell, while V_i represents the portion of the cell's volume occupied by phase i . The sum of all volume fractions within the cell totals 1.

In the numerical setup, the time step is set to 0.01 seconds, and the SIMPLE algorithm is used to couple the pressure and velocity equations.

NUMERICAL SCHEME

The schematics of the solution domain and its boundaries are displayed in Fig. 3. The velocity inlet boundary condition is utilised for the inlet boundary, located 1L in front of the fore perpendicular of the ship. The inlet velocity is utilised for the top and bottom of the domain, which are located 1.5L and 2.5L from the centre of gravity, respectively. For the outlet boundary, the pressure outlet boundary condition is used; it extends 2.5L from the aft perpendicular of the ship. The width of the virtual tank is considered to be 2.5L, and for the side and symmetry boundaries of the domain, the symmetry plane is defined. To avoid boundary reverse flow effects, boundaries are extended, and as such, computations are not influenced by the boundary conditions [29,30].

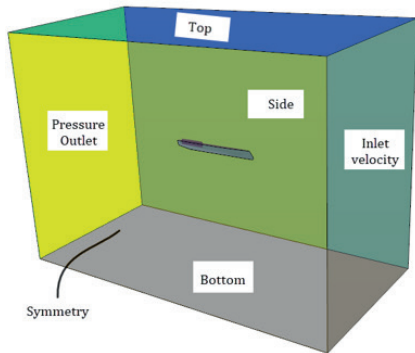


Fig. 3. Computational domain and domain boundaries

To enhance accuracy, mesh refinement is applied to the main hull, side hulls, and hydrofoil. Additionally, mesh refinement is carried out in the z -direction near the free surface. For the boundary layers of the hull and hydrofoil, a prism mesh with eight layers and a growth rate of is used. To better capture Kelvin waves, three tiers of subtracted blocks are implemented. The mesh configuration is shown in Fig. 4.

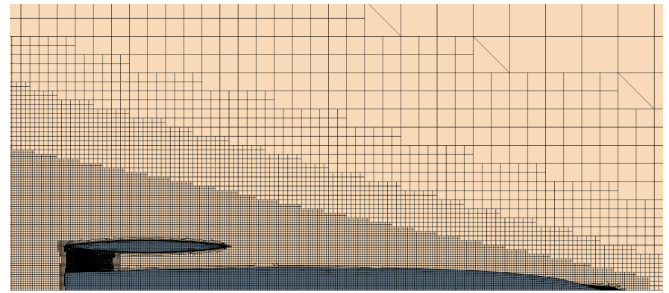
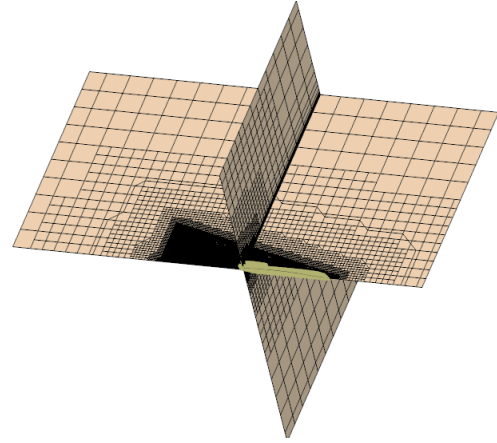


Fig. 4. Domain gridding and details of mesh configuration

MESH SENSITIVITY AND UNCERTAINTY ANALYSIS

This section presents a mesh study in calm water at a Froude number of 0.235. To ensure mesh independence, a convergence study is performed by varying the total resistance coefficient. Three mesh configurations, based on a refinement ratio of $\sqrt{2}$, are used to evaluate the results. Uncertainty analyses were performed using the Richardson method recommended by the ITTC (International Towing Tank Conference) [31]. Simulations with three grid plans (1, 2, and 3) were used to conduct the analysis. Following ITTC guidelines, uncertainty components for the iteration (U_I), grid (U_G), time step (U_T), and other parameters (U_P) were calculated, resulting in the total numerical uncertainty (U_{SN}):

$$U_{SN}^2 = U_I^2 + U_G^2 + U_T^2 + U_P^2. \quad (4)$$

In this study, only grid convergence and time step uncertainties were combined due to the unsteady numerical scheme, excluding other parameters. As a result, the uncertainty analysis focuses on discretisation, introduced as U_{GT} . The following formula was derived for this purpose:

$$U_{SN}^2 = U_I^2 + U_{GT}^2. \quad (5)$$

The iterative convergence is evaluated using the total resistance coefficient over the final two oscillation periods, showing a deviation of about 0.88% for SG1 (the drag value in grid plan 1):

$$U_I = \frac{1}{2(\tilde{S}_{\max} - \tilde{S}_{\min})} = 3.5e - 5. \quad (6)$$

Mesh plans and the uncertainty analysis for the trimaran simulations are shown in Tables 3 and 4. The convergence ratio () is defined as the ratio of changes between simulations with different grid plans:

$$R_G = \varepsilon_{21}/\varepsilon_{32} = (S_2 - S_1)/(S_3 - S_2). \quad (7)$$

The values of S represent the resistance coefficient outputs from the numerical simulations in the defined grid plan. A grid convergence factor (R_G) of less than 1 indicates monotonic convergence of the grid. Consequently, grid uncertainty can be estimated using the generalised relative error (RE) according to ITTC recommendations [31]:

$$\delta_{RE}^* = \frac{\varepsilon_{21}}{r^{P_G} - 1}. \quad (8)$$

Here, P_G represents the order of accuracy, and r denotes the refinement ratio ($\sqrt{2}$). The formula for P_G is given as follows:

$$P_G = \frac{\ln(\varepsilon_{32}/\varepsilon_{21})}{\ln(r)}. \quad (9)$$

Meanwhile, the correction factor can be expressed as

$$C_G = \frac{r^{P_G} - 1}{r^{P_{Gest}} - 1}. \quad (10)$$

Grid verification based on the drag coefficient is shown in Table 8. The order of accuracy, P_G , is 4.89, exceeding the theoretical value of 2, and the convergence factor, C_G , is 4.45, indicating solutions that are outside the asymptotic range. F_s is calculated using the following equation:

$$F_s = \begin{cases} 9.6(1 - C_G)^2 + 1.1 & |1 - C_G| < 0.125 \\ 2|1 - C_G| + 1 & |1 - C_G| \geq 0.125 \end{cases} \quad (11)$$

The uncertainty of the grid and time step U_{GT} is calculated by

$$U_{GT} = F_s |\delta_{RE}^*|. \quad (12)$$

Since the numerical simulation uncertainty U_{SN} is small (1.58% S1), it is possible to effectively capture differences in CT among various optimised models in the rest of this paper.

Tab 3. Details of simulation conditions and drag coefficients of trimaran model

Model velocity (m/s)	Grid plan	Total mesh	Time step	$C_T \times 10^{-3}(S)$
1.3 m/s	Grid 3	1.34 M	0.032 s	5.36
	Grid 2	1.82 M	0.02 s	5.56
	Grid 1	2.65 M	0.01 s	5.60

Tab. 4. Uncertainty analysis of the trimaran model

$\varepsilon_{21} \times 10^{-5}$	$\varepsilon_{32} \times 10^{-5}$	R_G	$\delta_{RE}^* \times 10^{-5}$	P_G	C_G	F_s	$U_{GT} \times 10^{-5}$	$U_I \times 10^{-5}$	$U_{SN} \times 10^{-5}$
-4.74	-25.8	-25.8	1.065	4.89	4.452	7.9	8.41	3.2	8.93

Tab. 5. Grid verification

$U_{GT}(\%S^1)$	$U_I(\%S^1)$	$U_{SN}(\%S^1)$
1.49	0.57%	1.58%

VALIDATION: WIGLEY TRIMARAN HULL

To verify the accuracy of the numerical model, the resistance of the simulated trimaran hull is compared with the wave-making resistance of a Wigley hull trimaran. The experimental data for this comparison were obtained by Battistin [32]. The geometry of the Wigley hull is provided by

$$y = B/2 \left(1 - [2x/L]^2\right) \left(1 - [z/T]^2\right).$$

In the simulation, the main hull of the trimaran is twice as long as the outriggers. The outriggers are 1.219 metres long, with a length-to-beam ratio of 10 and a beam-to-draft ratio of 1.6. The main hull measures 2.438 metres in length.

The midsections of the central hull and the outriggers are spaced longitudinally by 0.25L, with the outriggers placed at a transverse distance of 0.3L from the main hull's centre plane. The configuration and hull shape of the Wigley hull trimaran model are depicted in Fig. 5.

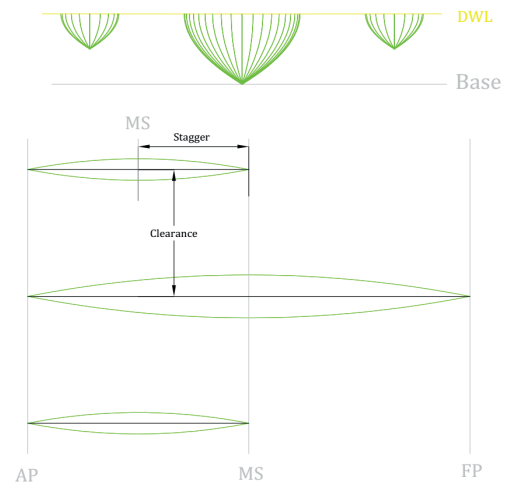


Fig. 5. Defined parameters in the Wigley trimaran vessel

The resistance coefficient is calculated across a range of Froude numbers from 0.2 to 0.5. The calculated resistance coefficients, along with experimental data [32], are presented in Fig. 6.

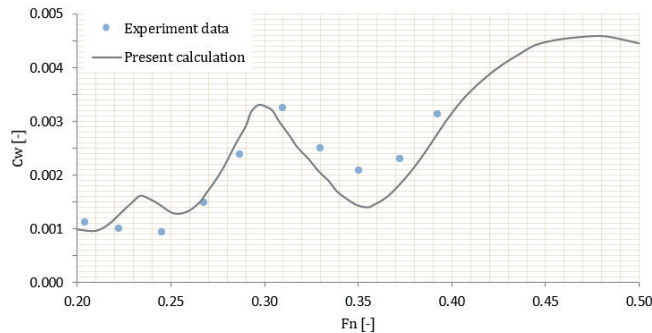


Fig. 6. The resistance coefficient obtained compared to the experimental results [26]

As shown in Fig. 6, the computed resistance coefficient matches the trend of the experimental data closely, demonstrating good agreement and indicating the accuracy of the numerical model.

OPTIMISATION METHOD

Optimising a fluid-exposed geometry involves a three-step procedure: reconstructing the geometry, applying a simulation solver, and using an optimiser. These steps are integrated into a multi-connection platform that forms an optimisation cycle. To use a direct optimiser, the optimisation platform must be automated [33,34]. In this case, PSO is employed; it is an evolutionary technique inspired by the behaviour of bird flocks. PSO operates similarly to a genetic algorithm, using a multi-point search that begins with a random set of designs, known as the swarm. Each design, or 'particle', has variable values that define its position in the swarm, known as the

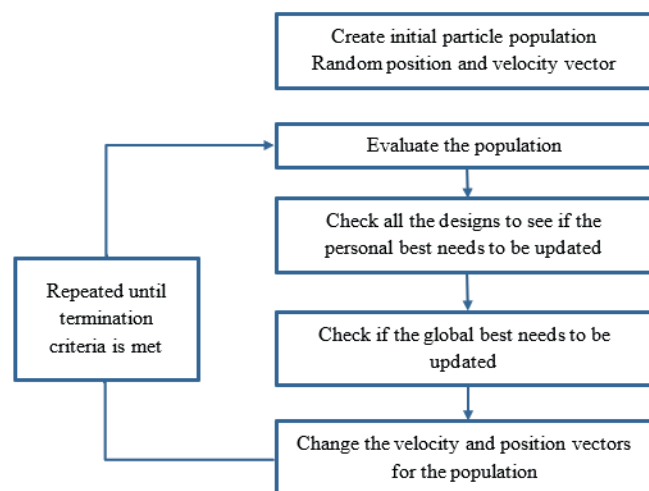


Fig. 7. Search process of the PSO algorithm

position vector. Along with this, each particle has a velocity vector. The algorithm tracks the best design in the swarm (global best) and the best design of each individual particle (personal best), with an optional local best that represents the best design in a neighbourhood around a given particle. New designs are generated by moving particles through the design space and adjusting their velocity vectors based on the global, personal, and local bests [25]. The search process of the PSO algorithm is illustrated in Fig. 7.

The population size is set to 16, indicating the number of designs assessed and explored in each cycle (generation) [34]. The search will be conducted over 16 cycles for this generation. All acceleration constants for the global best, local best, and personal best are set to 2. The three design variables involved in the optimisation are shown in Fig. 8. Additionally, these parameters are continuous and predetermined.

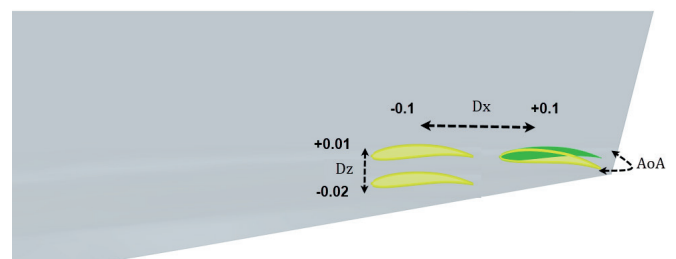


Fig. 8. Three design variables for optimisation

RESULTS AND DISCUSSION

This section presents and analyses the results of the resistance performance for the examined trimaran. Numerical simulations were conducted using STAR CCM+ software [23,25], with the CFD solver implementing an automated mesh [33]. A total of 257 design evaluations were performed. Design assessment was based on the system behaviour, analysed after the optimisation process was completed. Variations in the objective function and the absence of significant changes were used as decision-making criteria. Fig. 9 shows the optimisation process history, while Fig. 10 provides performance assessment values. Additionally, Fig. 11 offers parallel information on the objective function and design variables, highlighting the optimal variables and the most effective design.

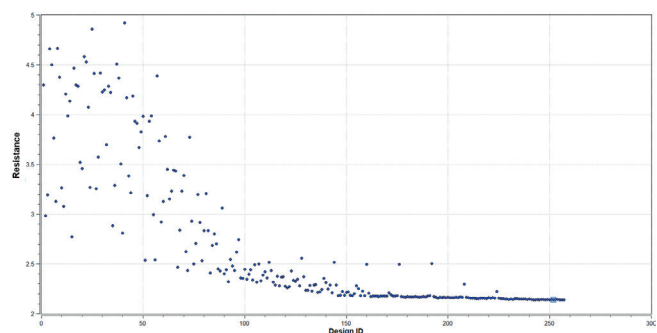


Fig. 9. The advancement of the optimisation process as it unfolds over time

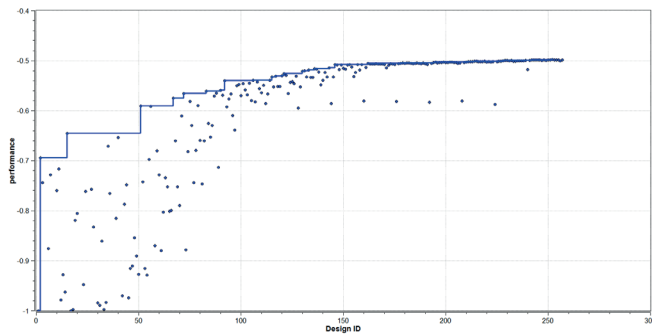


Fig. 10. History plot of performance rating of generated designs

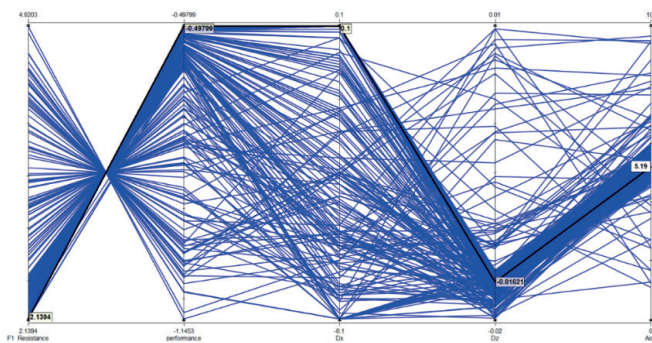


Fig. 11. Parallel plot of generated designs

The initial value of the objective function for the trimaran without a hydrofoil is 2.2402. When a hydrofoil is added and positioned correctly with an optimal AoA, this value decreases to 2.1394. Consequently, the objective function (resistance) improves by about 4.49%. This resistance reduction is considered quite remarkable compared to the shape optimisation technique for hull resistance reduction [35], which obtained a value of 3.14%, bearing in mind that applying change to the hull body is not as easy as installing hydrofoils. The optimised design variable values for the final hydrofoiled vessel are provided in Table 6.

Tab. 6. The refined values of the design parameters

No.	Parameter	Optimum value
1	Dx	0.1 m
2	Dz	-0.01621 m
3	AoA	5.19 deg.

Table 6 shows that the optimal AoA for minimising resistance is found within the middle range of the parameter. Additionally, the optimal longitudinal position of the hydrofoil is farther from midship, closer to the stern of the ship. Therefore, it is advised to position the hydrofoil towards the stern, as far back as the hull design permits.

To compare the flow fields around the initial hull and the trimaran with the appendage, Figs. 12, 13, and 14 are provided.

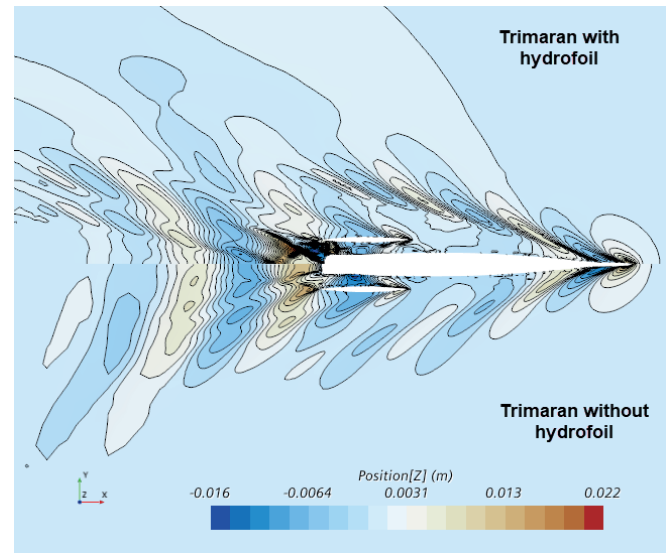


Fig. 12. Wave generation around trimaran with/without hydrofoil at design speed

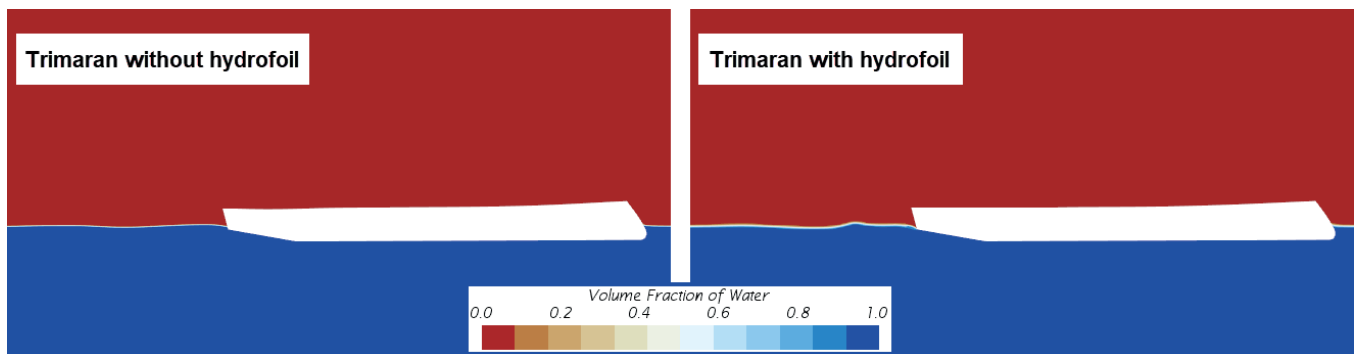


Fig. 13. Air/water fraction contour around trimaran with/without hydrofoil at design speed

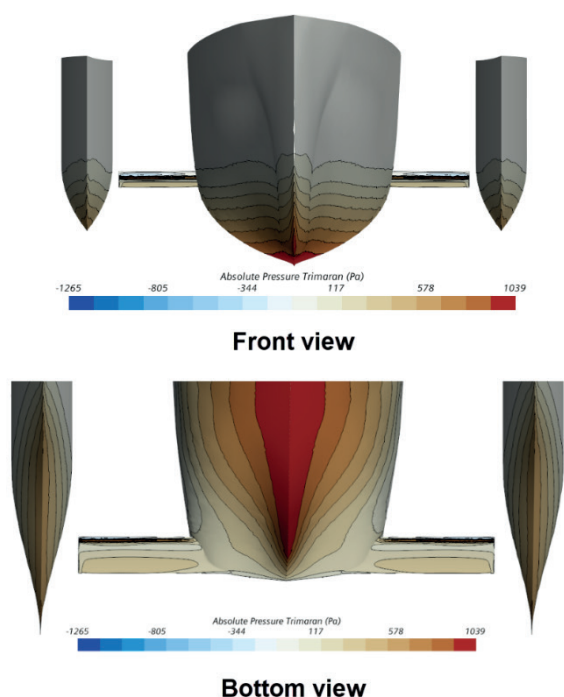


Fig. 14. Absolute pressure distribution near the hydrofoil at design speed

Fig. 12 shows wave generation around the hulls, with waves diverging at more varied angles for the trimaran with hydrofoils compared to the bare trimaran. Fig. 13 displays water fraction contours at design speed, where despite increased wave amplitudes, resistance is reduced. The interaction between the hulls also improves the trimaran's calm water performance. Fig. 14 depicts the absolute pressure distribution, indicating that the optimal hydrofoil position and AoA positively affect the trimaran's performance and pressure distribution.

The optimisation results for hydrofoil-equipped trimarans are highly sensitive to small variations in design variables such as the angle of attack and hydrofoil position. Small changes in these parameters can result in large variations in lift, drag, and overall resistance, underscoring the need for precise control and tuning. Sensitivity analysis is essential to identify the range of optimal settings and ensure that the vessel performs efficiently across a variety of conditions, as even slight deviations from the optimal design can lead to significant performance losses.

CONCLUSIONS

This study presents a comprehensive optimisation approach for the installation of a hydrofoil on a trimaran vessel, utilising computational fluid dynamics (CFD) analysis. The methodology involves simulating the trimaran with and without the hydrofoil to assess the total resistance in calm water conditions. The primary objective is to minimise resistance by optimising the hydrofoil's position and AoA,

specifically focusing on a NACA6612 hydrofoil mounted in the aft region, which can be adjusted from 1 to 10 degrees. A mesh sensitivity analysis is conducted based on the results of the resistance coefficient of a KCS (Kriso Container Ship) vessel, and a validation case is presented based on the resistance coefficient of a Wigley hull, indicating good accordance.

The optimisation process is facilitated through a multi-disciplinary optimisation (MDO) platform, integrating STAR-CCM+ software with a particle swarm optimisation (PSO) algorithm. Pre-processing tasks include configuring the hydrofoil's setup on the hull, conducting CFD simulations, and refining the optimisation settings. HEEDS MDO software orchestrates the management and integration of these tasks, while the numerical simulations are carried out using the Reynolds-averaged Navier-Stokes (RANS) equations, employing a k-epsilon turbulence model and a volume of fluid (VOF) scheme for capturing free-surface effects.

The study determines that the optimal placement for the NACA6612 hydrofoil is closer to the stern, rather than midship, with an ideal AoA of 5.19 degrees. This setup yields a 4.49% reduction in the total resistance of the trimaran, highlighting significant efficiency improvements. This resistance reduction is considered quite remarkable compared to the shape optimisation technique for hull resistance reduction [35], which obtained a value of 3.14%, bearing in mind that applying change to the hull body is not as easy as installing hydrofoils. The research suggests that future optimisation studies could expand on additional hydrodynamic aspects, such as seakeeping, to further refine the hydrofoil performance and its impact on vessel behaviour in various sea conditions.

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