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THE HYDRODYNAMIC IMPACT OF INTERCEPTORS AND BOW FENDER ON A HIGH SPEED DISPLACEMENT VESSEL

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Abstract: Substantial financial resources are dedicated to the design and research of new series of vessels, ensuring compliance with increasingly stringent emission regulations imposed every 5 years. With each design iteration, the final product becomes more energy efficient with a better hull shape, better fuel consumption and improved adaptability for a wide range of applications. For existing vessels, the challenge of increasing energy efficiency is constrained due to lower market demand for vessel modification, limited flexibility in comparison to new projects and budget limitations. In the present paper, the objective is set to analyse and improve the hydrodynamic flow for a small high speed displacement vessel, with the implementation of solutions that bring small changes in vessel design. Among the available options, active interceptors were chosen for further investigation. Mounted in the transom, this control system deploys a plate as an extension of the transom, generating a pressure area that creates a vertical force, thereby assisting in the correction of the trim angle. The investigation used Computational Fluid Dynamics (CFD) method, due to the speed and cost-effectiveness, when compared to an experimental method. To capture the viscous flow development around the hull, the Reynolds-averaged Navier-Stokes (RANS) equations were solved, and the free surface was discretized based on the volume of fluid. To establish a baseline for comparing the impact of the interceptor, a set of seven numerical simulations was conducted for the bare hull of a high-speed displacement pilot boat. Subsequently, the initial results revealed that, within the range of Froude number between 0.19 and 0.74 corresponding to the ship speed regime, the hull has a trim by the stern, generating a significant bow wave and causing a spray effect on the fore. Based on these first results, several solutions were modeled to improve the flow at the bow at a higher speed. With an average improvement of 1.3% in total resistance and reduced spray effect, the selected configuration, comprising a pipe and a fender, was further considered in the analysis. For the hull with the proposed bow configuration, in the transom area, the interceptor blade was extended across the entire transom edge. The effect on the flow was systematically investigated for different interceptor heights, which led in changes of trim angle and total resistance.
Key words: CFD, RANS, high speed displacement, interceptor, fender.

1. INTRODUCTION

In recent years, there has been a notable emphasis on achieving high speeds across various types of vessels, including passenger boats, Search and Rescue (SAR) et.al., to fulfill diverse requirements. A critical aspect of boat design involves power prediction, with a particular focus on hydrodynamic optimization to enhance efficiency, a topic that has garnered increased attention across policies and measures regarding reducing emissions and transitioning to a blue and sustainable economy.

Vessels operating at high Froude numbers experience dynamic motions which lead to increases in total resistance and fuel consumption. These motions are induced by dynamic forces acting on the hull, particularly affecting the wetted surface area. Sinkage and trim values show rapid changes within the Froude number range of 0.4 to 1.2, specific to high-speed displacement boats [1]. These changes directly impact the boat resistance, where the hull must overcome the increasing wave resistance by using an exponential amount of energy, consequently increasing fuel consumption. For already-built boats operating within this Froude range, minor modifications to the hull can be made to enhance energy efficiency. Without major hull form changes, the solution to increase the hydrodynamic performance resembles in attaching various energy saving devices to the hull, which should modify the flow. The interest in improving hull performance led to diverse energy-saving devices for hulls, with numerous studies validating their effectiveness. These devices can be divided into two categories: static and dynamic. Static devices, like stern flaps [2-5], wedges [6], bow fenders, and hull vanes [6], [7], remain fixed and primarily influence trim angles. Dynamic devices, such as interceptors [8-10], and trim tabs [11], adjust their position and exert a more active control over trim. Both types have been shown through experiments and simulations to reduce resistance, offering a promising path to fuel savings. Among these options, interceptors stand out for their versatility and affordability. Available in various sizes, these devices offer affordability and ease of installation, making them an attractive choice for boat owners seeking to boost fuel efficiency. Installed on the transom, interceptors release a plate into water, generating a force that counteracts the trim angle. In addition to unfavorable trim angles, high-speed displacement boats generate significant bow wave, which can be deflected with a bow spray rail.

The current research investigated how such an interceptor affects resistance. Improving the energy efficiency for a 12-m fast displacement hull involved a comprehensive analysis of flow characteristics. The vessel, operating in the 0.19-0.74 Froude number range, faced challenges with trim angles, resistance, and bow wave formation. Initial investigations focused on bow wave mitigation. Seven speed tests (2-8 m/s) were conducted to assess the wave's impact. Subsequently, a systematic study evaluated various bow appendiges, ultimately identifying a configuration that effectively reduced the bow wave wetted surface and resistance. With the optimized bow design, the focus shifted adding transom interceptors which are extending across the entire stern. Three interceptor heights were tested (1-3%B), demonstrating their capability to influence trim angles and total resistance. Initial full-span interceptor configurations were refined for optimal resistance performance. The final design adopted a configuration where the interceptors spanned one-third of the beam width (1/3B) and constituted with a height of 1% of the overall beam, maximizing effectiveness in reducing total resistance.

2. MATERIALS AND METHODS

To evaluate the hydrodynamic performance of the high speed displacement boat, we aimed to investigate parameters such as: total resistance, trim angle, pressure distribution, mass fraction, wave elevation, et.al. CADENCE/FineMarine software, a commercial Computational Fluid Dynamics (CFD) code, was used to analyze the flow behavior around the hull. This code employs an implicit Reynolds-averaged Navier-Stokes (RANS) solver, based on the finite volume method for discretizing the governing equations. For each generated volume of the domain, the solver calculates the velocity field from the momentum equations. The next step is to derive the pressure field by transforming the mass conservation equation into a pressure equation, to determine flow effects along the submerged hull. Moreover, the software solves additional equations for the development of turbulent flow. This study utilized the k-ω SST (Menter's Shear Stress Transport) turbulence model with wall functions for turbulence closure. To capture the free surface, a multi-phase flow approach based on the Volume of Fluid (VOF) method with high-resolution interface schemes was employed. This method models the incompressible and non-miscible fluid phases using separate conservation equations for each phase volume fraction. The pressure-velocity coupling is achieved through a face-based Semi-Implicit Method for Pressure Linked Equations (SIMPLE) algorithm. The software also has a 6 Degrees of Freedom (DOF) module to simulate the free motion of the ship, with the option to restrain specific degrees of freedom. Therefore, the model had the sinkage and pitch motions free to further understand the ship reaction in still water simulation.

The simulation model utilized a structured hexahedral mesh for the computational grid, generated using HEXPRESS™, a built-in module within CADENCE/FineMarine. This type of mesh offers efficient computation compared to unstructured meshes. The origin of the grid was positioned at the aft perpendicular (rearmost vertical part) of the ship model. The domain encompassed a volume around the ship, extending 3 ship lengths aft, 1.25 ship lengths fore, 2 ship lengths to the side, 2 ship lengths below the waterline and 1 ship length above the waterline. To improve computational efficiency while maintaining accuracy, a symmetrical boundary condition was implemented along the longitudinal centerline of the ship model. Other boundary conditions applied were: inlet, side and outlet planes as far field, top and bottom planes were set as prescribed pressure. Afterwards, boundary conditions were applied to the ship model, which was divided in two parts: deck and hull.

On the hull surface was applied the *no-slip* condition (to allow the fluid to adhere to the surface) while on the deck the *slip* condition was considered.

3. RESULTS AND DISCUSSION

3.1. Analysis of initial hull

The first phase of the study focused on the flow analysis for the bare hull of a 12-m pilot boat. This boat, with views depicted in Figure 1, features a design characterized by a hard chine along its sides, a deep V-shaped hull section amidships and a flat stern, intended to operate in a fast displacement regime. Detailed dimensions are provided in Table 1.

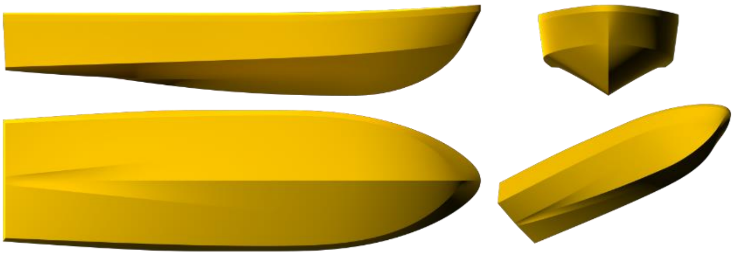


Fig. 1. Hull geometry

Table 1. Boat main characteristics

Dimension	Unit	Value
Length overall	[m]	11.9
Breadth overall	[m]	3.5
Draft	[m]	1.1
Depth	[m]	2.0
Displacement	[m^3]	17.7
Speed range	[m/s]	2-8
Fn number range	-	0.19-0.74

Analyzing the boat's behavior at a speed range between 2 and 8 m/s returned valuable insights into resistance performance and trim angle. As illustrated in Figure 2 and Figure 3, the transition from displacement to fast displacement regime is characterized by an immediate jump in trim angle, which in turn leads to an increase in resistance, showed in Figure 2.

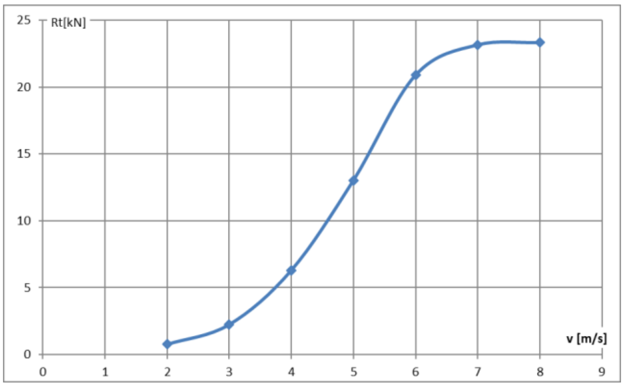


Fig. 2. Total boat resistance variation vs. speed

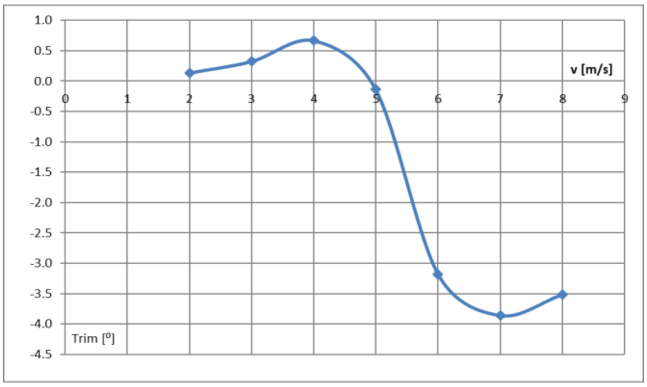
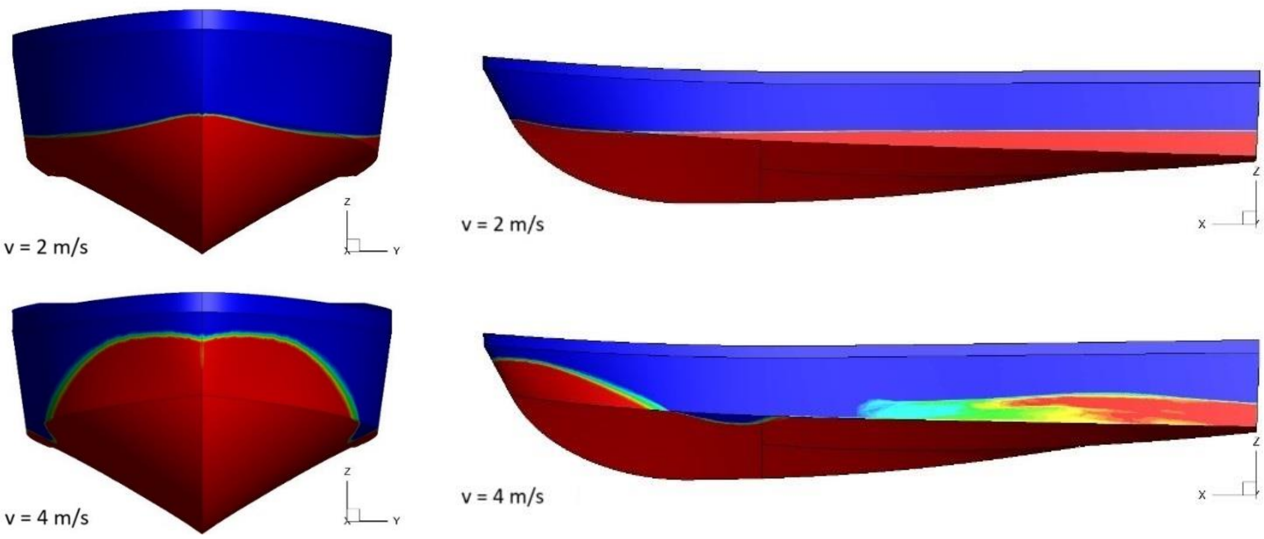


Fig. 3. Trim variation vs. speed

The range of speeds for which the hull was analysed reveals the dynamics of wetted surface. Figure 4 visualizes the changing fluid flow around the hull, where as the speed rises, the generated wave lengthens, but does not surpass the length of the boat. Additionally, the lack of a pronounced bow flare allows the wave to impact a larger bow area, causing "green water" (waves washing over the deck). The figure also shows the side chine's incapacity to effectively disperse fluid along the first half of the hull. At the same time, the flow visualization reveals spray forming along the hull sides. In Figure 5 is depicted the flow separation occurring at the stern and the development of the wave system. The dynamic trim occurring at high speeds, is in correlation with the wave trough positioned at the stern.



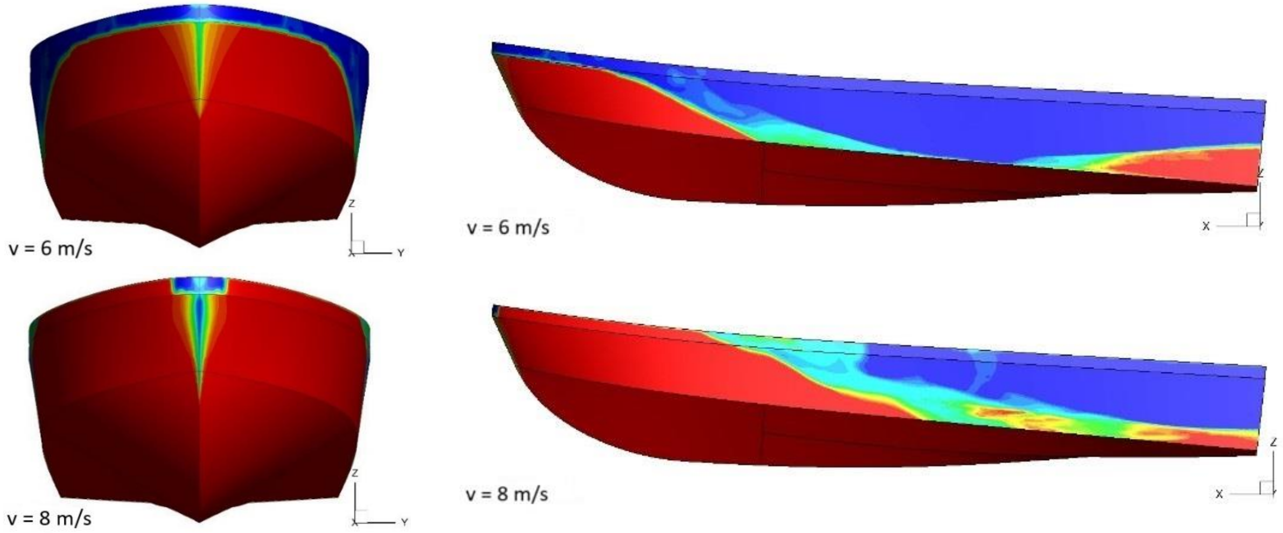


Fig. 4. Wetted surface for speeds 2, 4, 6 and 8 m/s

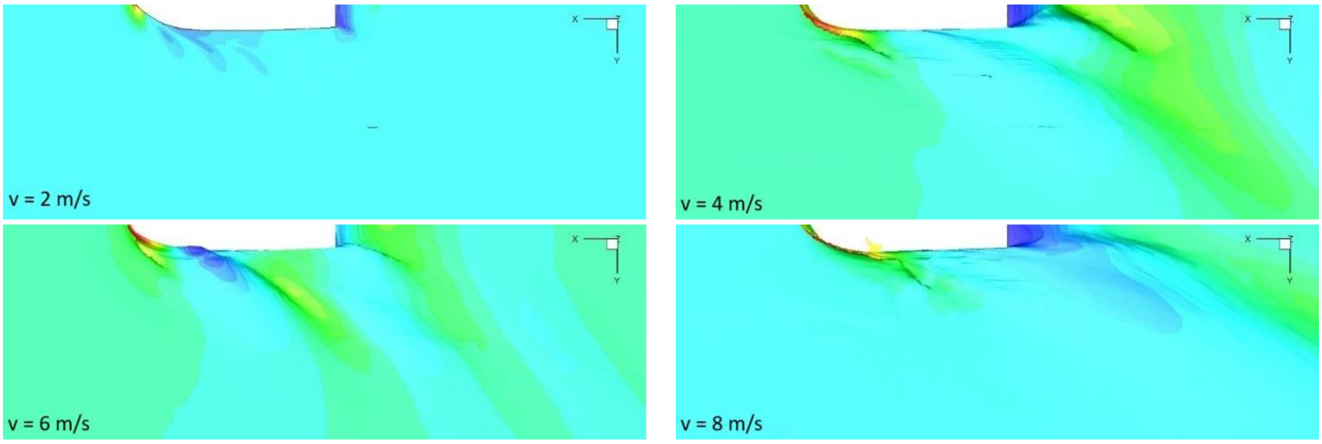
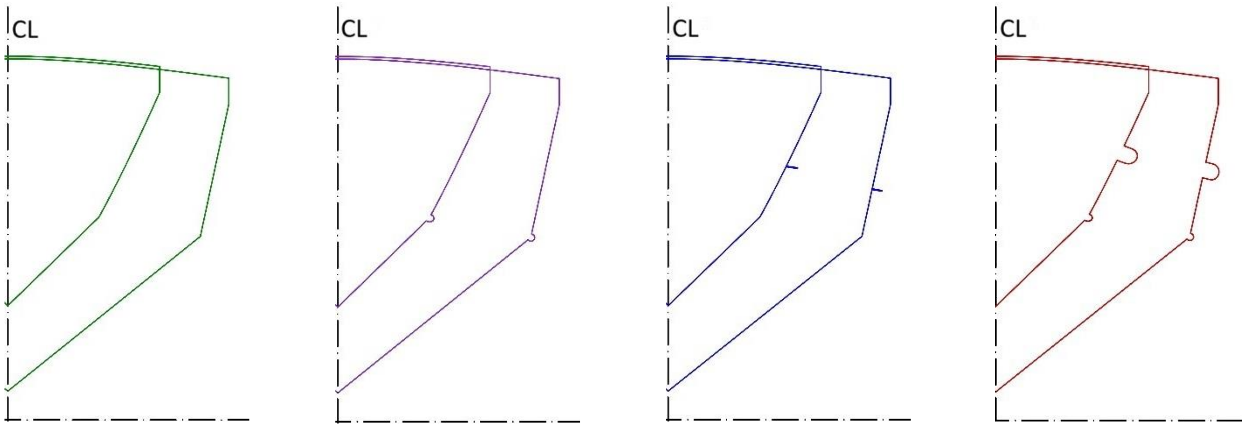


Fig. 5. Wave topology for speeds 2, 4, 6 and 8 m/s

3.2. Effects of distinct bow configuration

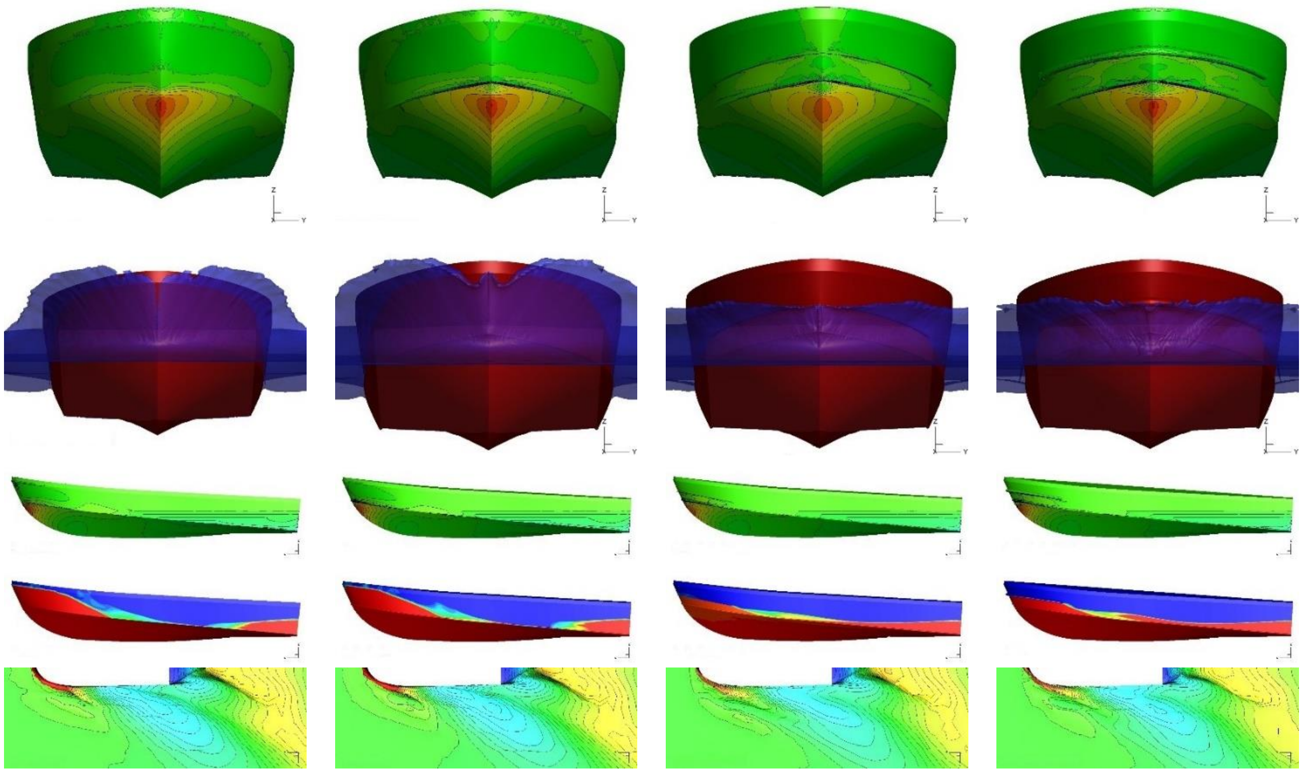
The study's subsequent objective involved identifying potential bow modifications for the 12-m pilot boat to enhance hydrodynamic performance within the 2-8 m/s speed range. These modifications were assessed for their impact on hull resistance, potentially leading to reductions in fuel consumption, and emissions and to mitigate operational challenges experienced by the vessel in fast displacement mode. The findings of Section 3 demonstrate the significant impact of wave generation at the bow on the 12-m pilot boat's overall hydrodynamic performance. At the range maximum speed of 8 m/s, the absence of a pronounced bow flare resulted in a considerably increased wetted surface, reaching close to 30% of the boat's lateral surface. Additionally, the data revealed a significant spray phenomenon at the bow, further indicating potential energy losses due to wave interaction and air entrainment. The subsequent analysis phase aimed to mitigate energy-intensive phenomena through minor hull modifications. In Figure 6 are illustrated 4 bow sections done for the studied configurations for their potential to control fluid flow and reduce spray. Therefore, Figure 6(a) represents the two transversal sections made at the bow for the initial ship model configuration, Figure 6(b) is the pipe along the chine edge, Figure 6(c) has a perpendicular strip on the bow and Figure 6(d) is a combined pipe-and-fender setup.

Analysis of the acquired hydrodynamic data revealed the influence of the implemented bow configurations. Figure 7 presents a series of visualizations for: dynamic pressure on the bow, wave deflection, dynamic pressure on the side, wetted surface area, and finally, wave topology. These visualizations collectively illustrate the modifications of boat geometry. At the speed of 6 m/s, the images reveal the impact of geometry on hydrodynamic performance. Through numerical simulations, we can observe an improvement in hydrodynamic performance at a speed of 6 m/s for the "Hull with bow strip" geometry. This trend continues for the last proposed configuration, i.e. "Hull with pipe chine and fender," which led to the selection of this final geometry for further optimizations. Furthermore, within the investigated speed range, the data presented in Table 3 indicate an average reduction of 1.30% in total resistance for this configuration compared to the bare hull.



(a) Initial hull | (b) Hull with pipe chine | (c) Hull with bow strip | (d) Hull with pipe chine and fender

Fig. 6. Bow configurations



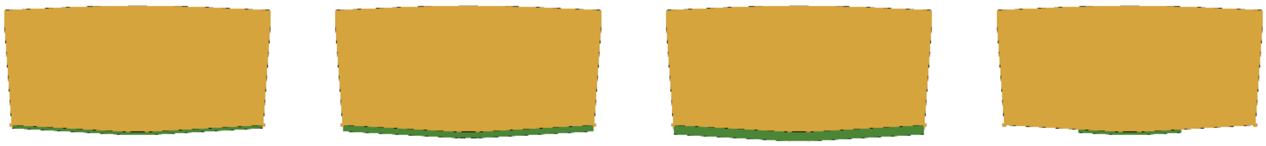
Initial hull | Hull with pipe chine | Hull with bow strip | Hull with pipe chine and fender

Fig. 7. Flow characteristics around the hulls

3.3. Effects of interceptors

Adding a chine pipe and bow fender demonstrated benefits in reducing wave/spray formation and drag, though the trim angle remained a concern. To further optimize performance, transom-mounted interceptors were introduced as a potential solution to the existing bow modification.

The analysis investigated interceptor heights of 35, 70, and 105 mm (representing 1%, 2%, and 3% of the boat's overall beam), extending across both the entire transom edge and a centered 1/3 beam-width configuration with a height of 35 mm. Figure 8 shows the representation of interceptors.



35 mm height | 70 mm height | 105 mm height | 35 mm height on 1/3B

Fig. 8. Interceptor configurations

The influence of interceptors primarily manifested in hull resistance and trim angle modifications. Table 2 presents the trim values obtained by numerical simulations, while Table 3 provides the relative difference in total resistance compared to the bare hull.

Table 2. Effect of interceptor on trim

No.	v [m/s]	Fn	Pipe&fender [deg]	i35 [deg]	i70 [deg]	i105 [deg]	i35-1/3B [deg]
1	2	0.19	0.11	0.22	0.28	0.33	0.16
2	3	0.28	0.28	0.52	0.67	0.79	0.40
3	4	0.37	0.52	0.95	1.27	1.49	0.71
4	5	0.46	-0.42	0.44	1.05	1.48	-0.04
5	6	0.56	-3.08	-1.48	-0.62	-0.01	-2.39
6	7	0.65	-3.86	-1.73	-0.71	-0.01	-2.88
7	8	0.74	-3.70	-0.83	0.42	1.37	-2.46

At lower speeds (up to 5 m/s) within the displacement regime, interceptors significantly impacted the vessel, increasing total resistance and trimming by bow up to 1.49 degree. Entering the fast displacement regime (above 5 m/s), a rapid switch in trim was observed, with the bare hull and pipe-and-fender configuration experiencing significant stern trim (reaching -3.83 degrees).
Notably, the full-width and full-height interceptor configuration maintained a level trim for the speed of 6 and 7 m/s. The study also revealed that at the highest speed tested (8 m/s), all interceptor configurations cause a trend towards bow trim.

Table 3. Effect of interceptor on boat total resistance

No.	v [m/s]	Fn	Pipe&fender [%]	i35 [%]	i70 [%]	i105 [%]	i35-1/3B [%]
1	2	0.19	-7.12	27.35	54.94	78.78	11.44
2	3	0.28	-4.80	18.96	36.85	52.98	5.66
3	4	0.37	-0.05	8.02	11.54	17.61	4.69
4	5	0.46	0.24	2.71	5.75	8.77	3.28
5	6	0.56	-0.47	0.97	3.70	6.45	-1.52
6	7	0.65	-1.97	3.38	8.60	12.47	0.29
7	8	0.74	5.08	15.39	20.28	12.95	9.35

Figure 9 presents a comparative analysis of total resistance and trim curves across the investigated speed range. The figure includes data for the bare hull, the hull modified with a chine pipe and bow fender, and all interceptor configurations subsequently added to the modified hull.
Of particular interest, configuration i35-1/3B (interceptor height of 35 mm, extending over 1/3 of the beam), when combined with the pipe and fender, achieved the most significant reduction of total resistance, i.e. 1.52% surpassing the 0.47% reduction obtained through the pipe and fender modifications alone.

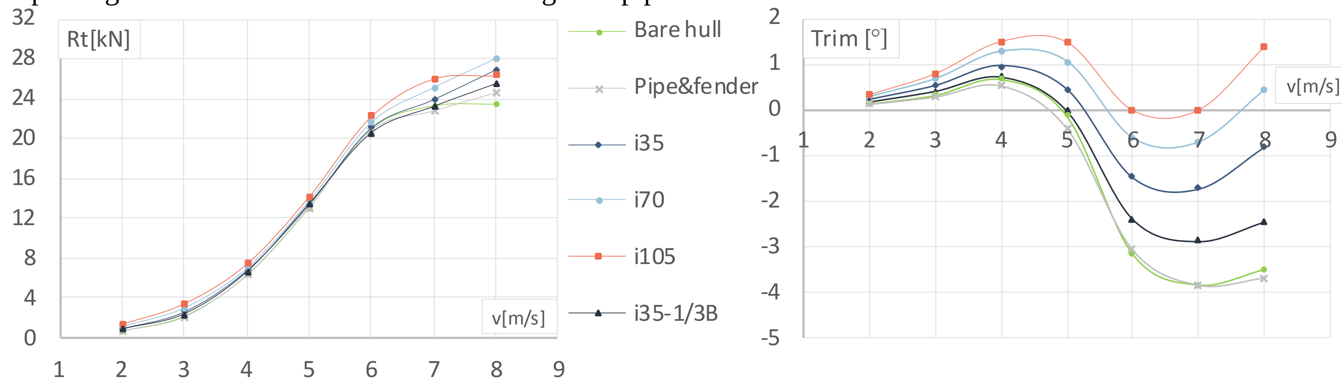


Fig. 9. Variation of resistance and trim for the proposed versions

4. CONCLUSIONS

The objective of this study was to enhance the energy efficiency of a 12-meter pilot boat hull, particularly focusing on its performance in the fast displacement regime. The methodology employed involved a meticulous analysis of the hull's hydrodynamics, aiming to identify areas for improvement within given constraints on hull form adjustments.
Initial hydrodynamic modeling was conducted utilizing RANS (Reynolds-averaged Navier-Stokes) simulations

with CADENCE/FineMarine software. This phase of the study yielded important data concerning the bare hull's characteristics across a range of speeds from 2 to 8 meters per second. Key parameters such as total resistance, trim, wave patterns, dynamic pressures, and wetted surfaces were assessed in order to understand the hull's behavior under different operating conditions.

The analysis of this data revealed certain challenges, particularly concerning issues related to green water and spray, which can significantly impact the vessel's performance and energy efficiency. Consequently, the study pivoted towards exploring solutions aimed at mitigating these challenges, with a specific focus on the integration of energy efficiency devices.

Three distinct configurations were proposed and evaluated for the investigated model. These configurations were designed to address the identified issues while adhering to the constraints imposed on hull form adjustments. Through rigorous evaluation and comparative analysis, one particular configuration emerged as significantly superior in terms of its effectiveness in reducing wetted surface and spray.

The selected configuration demonstrated an average reduction in total resistance of 1.30%, indicating a notable improvement in the energy efficiency of the pilot boat hull. This reduction in ship resistance signifies a decrease in the power required to propel the vessel through water, thereby enhancing its overall performance and fuel efficiency. To further optimize hydrodynamic performance, transom-mounted interceptors were introduced as trim control devices on the improved bow version of the model. Four interceptor variations were tested: 35 mm, 70 mm, 105 mm across the bottom edge, and 35 mm extending over 1/3 of the beam.

Results showed that the hull maintained a 0 degree trim at 6 and 7 m/s when the interceptors were deployed at 105 mm, and an increase in total resistance. The 35 mm, 1/3 beam-width interceptor demonstrated the lowest resistance increase. Significantly, this configuration resulted in a 1.52% reduction in total resistance compared to the bare hull at 6 m/s, indicating potential fuel savings when operated at this speed, demonstrating promising results in enhancing hydrodynamic performance.

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Conflicts of Interest: There is no conflict of interest.

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