

CFD-based stepwise integration and analysis of hull appendages on the resistance performance of a displacement vessel

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Abstract

This study presents a comprehensive numerical investigation into the hydrodynamic effects of commonly adopted hull appendages, which are the bulbous bow, skeg, and sonar dome, on a displacement ship operating across a wide Froude number range ($Fr = 0.16$ to 0.41). Simulations were conducted using Reynolds-Averaged Navier–Stokes (RANS) equations in combination with the Volume of Fluid (VOF) method to capture free-surface effects. A four-stage stepwise configuration scheme was employed: bare hull, hull with bulbous bow, with bulbous bow and skeg, and finally the fully appended hull including the sonar dome. Results indicate that the bulbous bow contributed the most significant reduction in total resistance, which is up to 8.62% at $Fr = 0.26$, through wave interference and improved pressure distribution. The skeg aided aft-body flow alignment while the sonar dome showed negligible effect on resistance within typical operating conditions. All appended configurations exhibited increased frictional resistance due to surface area growth, with the full configuration showing an average increase of 6.97%. However, these increases were offset by considerable reductions in pressure resistance, particularly in transitional speeds, with a maximum pressure drag reduction of 29.03% at $Fr = 0.24$. The novelty of this study lies in its systematic, configuration-based evaluation of multiple appendages under consistent CFD conditions, enabling clear quantification of trade-offs between frictional and pressure resistance. The findings offer practical insights into appendage integration strategies for performance optimization in displacement vessels and guidelines for naval architects in selecting and integrating appendages to optimize resistance characteristics during the early design stages of displacement vessels.

Keywords: Ship resistance, Hull appendages, Bulbous bow, Skeg, Sonar dome, CFD

1. Introduction

The investigation of ship appendages has expanded considerably over the decades, integrating disciplines such as CFD analysis, experimental validation, and machine learning to enhance vessel performance. Modern ship appendages, including rudders, bilge keels, stabilizer fins, and sonar domes are now viewed as integral to not only maneuverability but also resistance management and flow optimization.

The foundational understanding of ship resistance was significantly shaped by early experiments, particularly those conducted by William Froude, who introduced the concept of separating resistance into frictional and residuary components. This framework laid the groundwork for analyzing the effects of appendages on overall hydrodynamic performance. Building upon these principles, organizations such as the International Towing Tank Conference (ITTC) established standardized testing and evaluation procedures, enabling consistent and comparative assessments of appendage-induced resistance across different vessel configurations.

Research by Molland et al. [1] showed how rudders and bilge keels influence boundary layer behavior and contribute to wave-making drag. Carlton [2] highlighted the complex interference effects between rudders and propellers, pointing out risks such as cavitation caused by misalignment. Larsson and Raven [3] helped validate CFD models through rigorous comparison with empirical towing tank data. Toxopeus et al. [4] revealed that even minor geometric changes in appendages can influence local flow fields using overset mesh techniques. Di Mascio et al. [5] found that rudder–skeg positioning can mitigate yaw through controlled flow alignment under oblique conditions.

Díaz-Ojeda et al. [6] and Lu et al. [7] investigated the refinement of bulbous bow designs using computational fluid dynamics (CFD) coupled with genetic optimization techniques. Their results revealed that carefully optimized bow shapes can lead to meaningful reductions in wave-making resistance. Wu et al. [8] and Pei et al. [9] examined sonar dome configurations with a focus on achieving an effective trade-off between hydrodynamic efficiency and acoustic functionality. Their analyses emphasized the importance of surface shaping and placement in minimizing drag while preserving sonar clarity. Mandru and Pauraru [10] and Ye et al. [11] conducted CFD-based studies on various skeg designs, demonstrating that specific geometries can reduce resistance while maintaining adequate course-keeping and directional stability.

Fahrholz and Caprace [12] explored the application of neural networks in estimating appendage-induced drag, leveraging geometric input data to deliver accurate predictions with minimal computational cost. Their approach highlights the potential of AI

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tools in streamlining early-stage hydrodynamic assessments. Hirdaris et al. [13] introduced a digital twin framework that integrates real-time monitoring and CFD analysis to track appendage behavior dynamically during vessel operation, enhancing responsiveness to environmental changes. Çelik et al. [14] employed a surrogate model-driven optimization strategy to address multiple hydrodynamic objectives simultaneously, including drag minimization and maneuvering performance. In parallel, White et al. [15] implemented a hybrid RANS–LES technique to investigate unsteady flow phenomena around appendages under wave conditions, capturing complex turbulence interactions with high fidelity.

Building on previous work, additional studies have examined integrated appendage design strategies. Wang et al. [16] conducted CFD-based optimization of rudders in combination with energy-saving devices (ESDs), identifying configurations that reduce overall resistance and enhance propulsion effectiveness. Çelik [17] investigated the interaction between rudders and ducts, demonstrating that improved wake uniformity and reduced vibration could be achieved through coordinated shaping. Liu et al. [18] proposed a comprehensive design methodology where hull geometry and appendage placement are simultaneously refined to improve hydrodynamic coherence. Hu et al. [19] analyzed how different skeg placements affect stern-region flow characteristics and identified design adjustments that help minimize vortex formation and hydrodynamic noise.

Several studies have explored the performance of sonar domes in balancing hydrodynamic resistance and acoustic efficiency. Sharma and Sha [20] investigated how different geometric features of sonar domes—such as curvature and structural composition—affect flow disruption and acoustic signal quality. Shao et al. [21] expanded this by analyzing pressure recovery and vibration effects linked to dome shaping under varied flow conditions. Collectively, these investigations demonstrate that the integration of sonar domes with the hull form plays a critical role in determining both fluid flow patterns and the clarity of sonar performance, underscoring the need for design solutions that address both hydrodynamic and acoustic considerations simultaneously.

More recent contributions have advanced the understanding of appendage performance through diverse methods and applications. Hu et al. [22] investigated asymmetric rudder shapes using genetic algorithms and CFD simulations, highlighting improvements in wake symmetry and maneuvering efficiency. Korkut [23] examined fairing designs for shaft brackets, demonstrating smoother propeller inflow and reduced turbulence. Yao et al. [24] evaluated stabilizer fin dynamics in wave environments through CFD, revealing the impact of wave-induced loads on performance. Sumarsono et al. [25] and Villa et al. [26] provided valuable experimental and numerical validation of drag increases due to appendages, reinforcing the importance of physical testing alongside simulations. Innovations by Morales et al. [27] and Troll et al. [28] introduced flow-adaptive geometries and real-time fluid–structure interaction (FSI) monitoring, offering new approaches for responsive appendage behavior. Additionally, Yang et al. [29] applied machine learning for early drag estimation based on appendage design, while Liang et al. [30] developed reinforcement learning-based control systems for active stabilizer fins to enhance hydrodynamic stability and efficiency.

Recent studies have also expanded the analysis of appendage effects through modern CFD-based approaches. Chen et al. [31] investigated hydrofoil appendages positioned at the bow and stern of high-speed vessels using RANS-based CFD simulations, reporting a resistance reduction of up to 14.55% due to improved pressure distribution and wave interaction. Song et al. [32] analyzed the combined effects of interceptors and stern flaps, finding that integrated appendages reduced total resistance by up to 3% and enhanced motion performance in regular waves. These contributions highlight the growing relevance of appendage integration and validate the continued need for configuration-specific hydrodynamic evaluation.

The integration of hull appendages plays a crucial role in enhancing hydrodynamic performance, particularly in reducing resistance and improving wake flow. Ye et al. [11] used CFD to evaluate the influence of multiple appendages – such as sonar domes and stern fins – on maritime surveillance vessels, finding that effective combinations help stabilize pressure fields and reduce drag. Similarly, Campana et al. [33] demonstrated that integrated appendage geometries exhibit non-linear interactions, influencing flow characteristics depending on design arrangement.

Specialized appendages have also been examined for their hydrodynamic and acoustic effects. Wu et al. [8] showed that wave-piercing sonar domes with optimized shapes reduce boundary-layer separation and maintain acoustic clarity. Torckler [34] used CFD to analyze streamlined stern appendages, finding they minimize wake turbulence and pressure drag with minimal friction penalties.

While many previous studies have focused on the performance of individual appendages in isolation, relatively few have conducted comparative analyses under unified simulation frameworks. The lack of standardized conditions across studies makes it difficult to quantify the combined hydrodynamic effects of multiple appendages. This gap highlights the need for integrated evaluations that apply consistent CFD setups to systematically assess appendage performance. Thus, this study aims to systematically evaluate the resistance characteristics of a displacement-type hull with commonly used appendages, including a bulbous bow, skeg, and sonar dome. A stepwise simulation approach is adopted to isolate their individual and cumulative effects under controlled CFD conditions, covering a representative Froude number range of 0.16 to 0.41. Unlike previous studies that assess single appendage types, this work offers a view of integrated appendage design and its implications for resistance optimization.

2. Methodology

2.1 Theoretical background of ship resistance

Ship resistance arises from multiple physical mechanisms that together determine the total hydrodynamic force opposing a vessel's motion in calm water. This total resistance (R_T) can be divided into several main components:

Friction Resistance (R_F): Due to viscous shear stress acting along the wetted hull surface, caused by the development of a boundary layer. The ITTC (International Towing Tank Conference) recommends estimating frictional resistance using the ITTC-1957 correlation line, defined by:

$$C_F = \frac{0.075}{(\log_{10} Re)^2} \quad (1)$$

Where C_F represents the frictional coefficient and Re is the Reynolds number based on vessel length and velocity.

The remaining resistance, often termed residual resistance, includes wave and pressure components and is commonly obtained by subtracting frictional values from the total measured resistance in model testing or simulation:

Form or Viscous Pressure Resistance (R_{VP}): Arises from pressure differences around the hull, particularly in regions with flow separation or abrupt geometry.

Wave-Making Resistance (R_W): Associated with the energy required to generate surface waves as the hull moves through water.

Appendage Resistance (R_{APP}): Additional drag caused by appendages such as rudders, brackets, bilge keels, and fins. Appendage resistance has become an increasingly important factor in total drag estimation, particularly for hulls with complex stern structures or multiple control devices. Interactions between appendages and the hull's near-wall flow can enhance turbulence, disrupt streamline patterns, and induce wake asymmetry, all of which contribute to increased resistance. The magnitude of these effects depends on appendage shape, orientation, and integration with the hull.

Air Resistance (R_{Air}): Due to aerodynamic drag on above-water structures, which is not considered in this analysis.

In this study, two main resistance components were focused, which are friction and pressure resistance. Hence, total resistance can be expressed as:

$$R_T = R_F + R_P = \frac{1}{2} \rho V^2 S C_T \quad (2)$$

$$R_T = \frac{1}{2} \rho V^2 S (C_F + C_P) \quad (3)$$

Where, ρ is water density (kg/m^3), V is vessel speed (m/s), and S is wetted surface area (m^2). C_T , C_F and C_P are total, friction and pressure resistance coefficients respectively.

Modern CFD tools facilitate detailed investigation of these resistance components. Using Reynolds-Averaged Navier-Stokes (RANS) solvers with multiphase modeling techniques like the Volume of Fluid (VOF), it is possible to simulate both viscous flow and free surface wave dynamics. By running comparative simulations with and without appendages, CFD enables a clear assessment of the added resistance each component contributes.

A solid grasp of these theoretical aspects is essential for effective hull and appendage design. In this work, resistance decomposition derived from CFD forms the basis for evaluating how appendages influence hydrodynamic performance and identifying opportunities for design refinement.

2.2 Model geometry and configuration

The hull geometry used in this investigation was modeled to resemble a typical mid-sized displacement vessel (approximately 65 m), adopting general form characteristics of Research Vessel (RV), which is normally operated at low Froude number (Fr). A three-dimensional CAD modeling approach was used to generate the base hull form, which incorporated realistic hydrostatic parameters including displacement, block and prismatic coefficients, and longitudinal center of buoyancy. These parameters were matched to those common in contemporary commercial ship designs to ensure geometric and hydrodynamic relevance. Thus, the model is scaled down to 1:10, which is 6.5 m in length.

Three commonly employed appendages were selected for analysis in this study: skeg, bulbous bow, and sonar dome or sensor transducer. All appendages were designed based on specifications aligned with ITTC guidelines and adjusted to maintain high fidelity in their geometric representation. The skeg was placed at the aft part of the vessel below the stern to strengthen the rear side. The bulbous bow is down and located foremost at the bow to counter wave resistance by generating bow wave to induce destructive interference, hence reducing resistance. Sonar dome or sensor transducer featured a hydrodynamically design appropriate for underwater instruments.

To systematically evaluate the resistance contribution of each appendage, a stepwise simulation scheme was adopted. This included: (1) the bare hull model, (2) hull with bulbous bow, (3) hull with bulbous bow and skeg, (4) hull with bulbous bow, skeg and sonar dome. This approach enabled accumulative analysis of hydrodynamic impacts associated with all components.

CAD models were exported in formats compatible with meshing tools to ensure clean surfaces and geometric continuity. Particular attention was given to appendage alignment, symmetry, and installation clearances to match operational realism. The particulars and geometry are presented in Table 1 and Figures 1 and 2.

Table 1 Hull Particulars Comparison

	Bare Hull	Hull with Bulbous Bow	Hull with Bulbous Bow and Skeg	Hull with Bulbous Bow, Skeg and Sonar Dome
LOA, m	6.500	6.500	6.500	6.500
LWL, m	6.467	6.467	6.467	6.467
L/B (Baseline)	4.822	4.822	4.822	4.822
B/T (Baseline)	4.438	4.438	4.438	4.438
Wetted Surface Area, m^2	9.446	9.634	9.716	9.756
Waterplane Area, m^2	7.099	7.099	7.099	7.099
Frontal Area, m^2	0.431	0.431	0.431	0.434
Block Coefficient, C_B	0.618	0.627	0.627	0.627

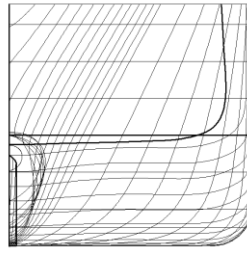


Figure 1 Body Plan

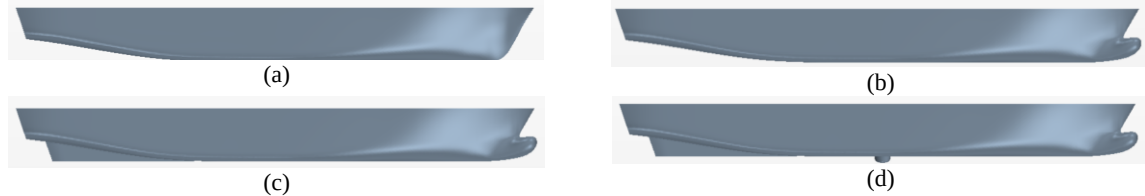


Figure 2 Profile of a) bare hull, b) bare hull with bulbous bow, c) bulbous bow with skeg, and d) all appendages – bare hull with bulbous bow, skeg and sonar dome.

2.3 CFD application

Computational Fluid Dynamics (CFD) with VOF is a branch of fluid mechanics that uses numerical methods and algorithms to analyze and solve problems involving fluid flow. It enables the simulation of fluid behavior in complex geometries and under varying physical conditions, eliminating the need for extensive physical prototyping or experimentation. The mathematical background is shown in equations (4) – (7).

Continuity Equation (Mass conservation):

$$\nabla \cdot \vec{u} = 0 \quad (4)$$

Navier–Stokes Equations (Momentum conservation):

$$\rho \left(\frac{\partial \vec{u}}{\partial t} + (\vec{u} \cdot \nabla) \vec{u} \right) = -\nabla p + \mu \nabla^2 \vec{u} + \vec{f} \quad (5)$$

Energy Equation (Heat transport):

$$\rho c_p \left(\frac{\partial T}{\partial t} + \vec{u} \cdot \nabla T \right) = k \nabla^2 T + \phi \quad (6)$$

Volume fraction function:

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha \vec{u}) = 0 \quad (7)$$

These equations describe how fluid particles move, interact with boundaries, exchange energy, respond to external forces, and free surface created.

The CFD process generally consists of three main stages. *Pre-processing*: Involves constructing the computational domain, generating the mesh, and defining physical models and boundary conditions. *Solving*: The numerical solver applies discretized forms of the governing equations using methods such as the finite volume or finite element technique. *Post-processing*: Results are visualized and interpreted through contours, vector plots, streamlines, and graphs, allowing for qualitative and quantitative analysis of the flow field.

At the core of CFD are mathematical formulations that represent the conservation of mass, momentum, and energy within a fluid system. These governing equations are typically expressed as partial differential equations and are solved using discretization techniques on computational grids or meshes.

The simulations were performed using the commercial CFD software STAR-CCM+. A consistent numerical formulation was adopted throughout the study, in which the momentum and turbulence transport equations were discretized using a second-order upwind scheme to ensure stable and accurate spatial resolution. This single discretization approach was applied uniformly across all configurations to maintain numerical consistency.

2.4 Numerical domain and grid dependency

CFD simulations were performed using a Reynolds-Averaged Navier-Stokes (RANS) solver, with the turbulence effects captured via the $k - \omega$ SST model, known for its balance between near-wall resolution and wake prediction as shown in equations (8) – (9). The SST $k - \omega$ model was selected due to its robustness in resolving near-wall boundary layers while preserving accuracy in the

free-stream region. It blends the standard $k - \omega$ model near walls with the $k - \varepsilon$ model in the outer flow, providing improved predictions of separation and adverse pressure gradients. This model has been widely validated for marine applications and was originally proposed by Menter [35]. The flow was treated as incompressible and multiphase, accounting for free surface deformation using the Volume of Fluid (VOF) method. An implicit unsteady solver was assigned with the objective of reaching a numerically stable steady-state solution, providing robustness to convergence in the presence of free-surface interactions. The computational domain extended longitudinally from 6 ship lengths upstream to 10 ship lengths downstream, with 5 times ship length for transverse and 2.5 times ship length for vertical boundaries to prevent reflection or blockage effects.

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_j)}{\partial x_j} = P_k - \beta^* \rho k \omega + \frac{\partial}{\partial x_j} \left[(\mu + \sigma_k \mu_t) \frac{\partial k}{\partial x_j} \right] \quad (8)$$

$$\frac{\partial(\rho \omega)}{\partial t} + \frac{\partial(\rho \omega u_j)}{\partial x_j} = \alpha \frac{\omega}{k} P_k - \beta \rho \omega^2 + \frac{\partial}{\partial x_j} \left[(\mu + \sigma_\omega \mu_t) \frac{\partial \omega}{\partial x_j} \right] + 2(1 - F_1) \rho \sigma_{\omega 2} \frac{1}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j} \quad (9)$$

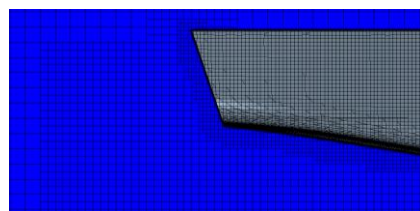
Where, ρ is fluid density, u_j is mean velocity component in the j -direction, μ is dynamic viscosity of the fluid, μ_t is turbulent viscosity, k is turbulent kinetic energy, ω is specific dissipation rate of turbulent kinetic energy, P_k is Production rate of turbulent kinetic energy, β, β^* are empirical model coefficients, α is the model constant related to production of ω , $\sigma_k, \sigma_\omega, \sigma_{\omega 2}$ are diffusion coefficients for k and ω , F_1 is Blending function between the standard $k - \omega$ and $k - \varepsilon$ models.

The mesh topology consisted of unstructured-trimmed hexahedral and prism layers, with local refinement around appendages, the hull surface, and the wake region. A grid independence study was conducted to confirm that resistance values remained within a 1% deviation across progressively refined meshes. Eight different refinement grids were created. Boundary conditions were defined as velocity inlet, pressure outlet, symmetry plane on centerline boundary, and no-slip conditions on the hull and appendages.

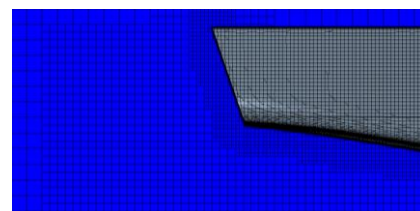
A grid dependency study was performed using eight mesh configurations, shown in Table 2, with consistent refinement blocks around the hull and varying levels of detail in the water column and wake regions. The refinement ratio ranged from 1.012 to 1.247, with an average of 1.146, indicating a gradual increase in resolution. This setup supports a structured analysis of grid convergence and ensures reliability in the final CFD results. The different grid generation techniques are shown in Figures 3 – 5.

Table 2 Grid Parameters Used in Mesh Convergence Study

Grid	1	2	3	4	5	6	7	8
No. of Refinement Blocks around Hull	3	3	3	3	3	3	3	3
Volume Growth Rate	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium
Surface Growth Rate	Medium	Medium	Slow	Medium	Slow	Medium	Slow	Medium
No. of Refinement Blocks for Water Column	-	1	1	2	2	2	2	2
No. of Refinement Blocks for Wake	-	-	-	-	-	1	1	2
No. of Cells (Millions)	4.270	4.322	4.763	5.902	6.615	8.247	9.076	10.902
Grid Refinement Ratio (RG)	-	1.012	1.102	1.239	1.121	1.247	1.100	1.201
Average (RG)	1.146							

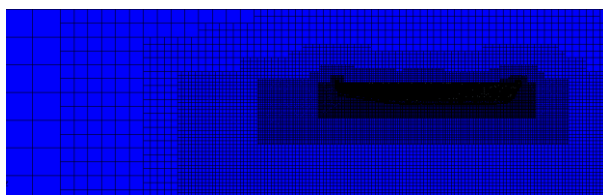


(a)

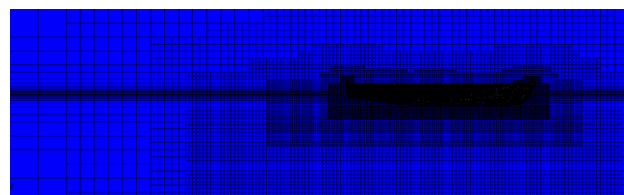


(b)

Figure 3 Grid with medium growth rate (a) and grid with slow growth rate (b).



(a)



(b)

Figure 4 Grid without free surface refinement (a) and grid with surface refinement (b).

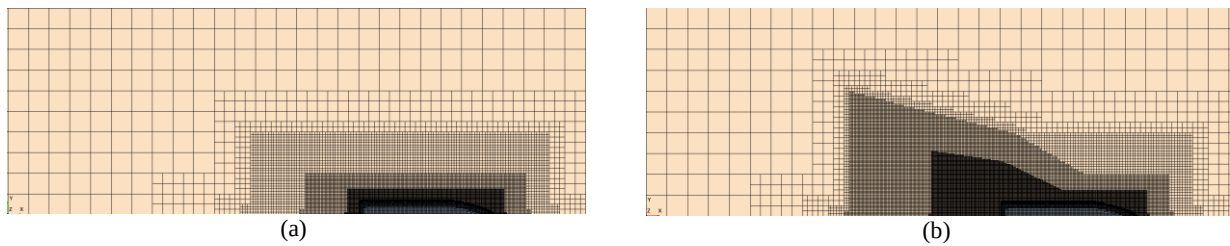


Figure 5 Grid without wake refinement (a) and grid with wake refinement (b).

A grid convergence study, see Figures 6, was performed using eight mesh levels to evaluate the sensitivity of total resistance to mesh refinement for $Fr = 0.16$. The resistance decreased significantly in the first three grids and began to stabilize thereafter. Between Grid 5 and Grid 8, the relative change remained below 0.2%, with Grid 6 exhibiting minimal variation compared to subsequent refinements. Based on these results, the solution was considered grid-independent beyond Grid 6.

Due to the absence of available experimental or benchmark data, this study relied exclusively on numerical simulations to assess resistance and flow characteristics. Therefore, internal consistency and computational robustness were prioritized to ensure the reliability of results.

A mesh sensitivity analysis was performed to verify that resistance predictions remained stable across different grid densities. The mesh independence was confirmed when total resistance varied by less than 1% between successive levels of mesh refinement as shown in Figure 7.

While the grid-independence study confirms that the numerical solution is insensitive to further mesh refinement, it should be noted that this assessment represents numerical fidelity rather than physical validation. In the absence of experimental or benchmark data for the present geometry, the grid convergence analysis serves only to ensure internal consistency of the computed results. Physical validation would require comparison against towing-tank measurements or standardized datasets, which are beyond the scope of this study.

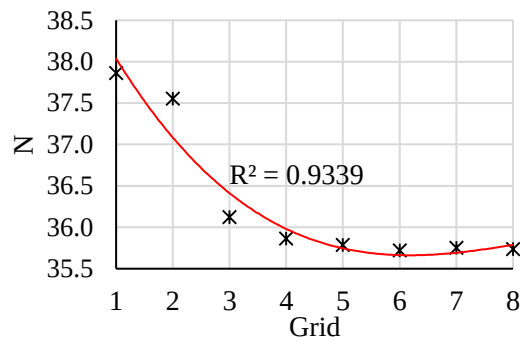


Figure 6 Total resistance vs speed for different grids.

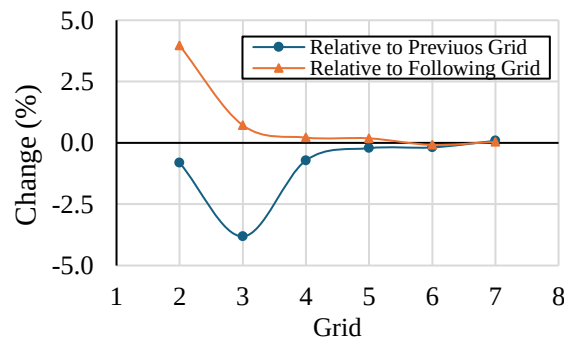


Figure 7 Total resistance vs speed for different grids.

3. Results

3.1 Resistance breakdown

Simulation conditions matched realistic operating speeds, covering a range of Froude numbers between 0.16 – 0.41 to assess performance across service conditions. Resistance was computed from shear (friction) and pressure forces on the wetted surface, and the incremental increase from each appendage was quantified. The analysis of resistance was conducted for each simulation configuration to quantify the individual and cumulative effects of appendages. Resistance was decomposed into its primary components: shear force, which is primarily due to friction along the wetted surface, and pressure force, driven by pressure distributions and hull shape interactions with the free surface. The bare hull served as the control baseline, against which the resistance values of subsequent configurations were compared.

The results, shown in Table 3 and, Figures 8 – 9, indicate that the incorporation of a bulbous bow yields the most distinct reduction in total resistance when considered independently, particularly within the transitional Froude number range (approximately $Fr = 0.24 - 0.33$). This improvement is attributed to the bow’s capability to alter wave-making patterns and enhance pressure distribution along the forward hull section. The addition of a skeg further contributes to resistance increase. While the sonar dome introduces a slight increase in resistance at lower speeds, it maintains acceptable behavior under cruise conditions and does not significantly compromise overall performance. On average, the fully appended hull configuration, which includes bulbous bow, skeg, and sonar dome, achieved a 2.53% reduction in total resistance relative to the bare hull baseline. These findings underscore the practical effectiveness of integrated appendage arrangements in enhancing hydrodynamic efficiency while preserving functional utility.

Table 3 Total resistance comparison

Total Resistance (N)									
Fr	V (m/s)	Re	Bare Hull	Bare Hull + Bulbous Bow	Rel. to Bare Hull (%)	Bulbous Bow + Skeg	Rel. to Bare Hull (%)	Bulbous Bow + Skeg + Sonar Dome	Rel. to Bare Hull (%)
0.16	1.30	8.026E+06	35.75	40.56	13.47	40.24	12.57	40.30	12.75
0.18	1.46	9.029E+06	45.96	49.34	7.36	49.74	8.23	49.48	7.65
0.20	1.63	1.003E+07	58.00	57.02	-1.69	57.06	-1.62	57.66	-0.59
0.22	1.79	1.104E+07	72.18	68.38	-5.26	68.67	-4.86	69.16	-4.18
0.24	1.95	1.204E+07	89.21	81.85	-8.25	82.56	-7.45	83.22	-6.72
0.26	2.11	1.304E+07	109.62	100.17	-8.62	100.89	-7.96	101.46	-7.44
0.29	2.28	1.405E+07	143.59	132.82	-7.50	134.48	-6.35	135.26	-5.80
0.31	2.44	1.505E+07	183.03	168.24	-8.08	168.77	-7.79	169.70	-7.29
0.33	2.60	1.605E+07	212.63	195.69	-7.97	195.18	-8.21	196.42	-7.63
0.35	2.77	1.705E+07	244.09	230.62	-5.52	230.89	-5.41	232.29	-4.83
0.37	2.93	1.806E+07	300.78	286.57	-4.72	291.43	-3.11	292.17	-2.86
0.39	3.09	1.906E+07	385.16	367.49	-4.59	370.79	-3.73	371.71	-3.49
0.41	3.25	2.006E+07	489.31	472.94	-3.35	477.02	-2.51	477.34	-2.45
Avg.					-3.44		-2.94		-2.53

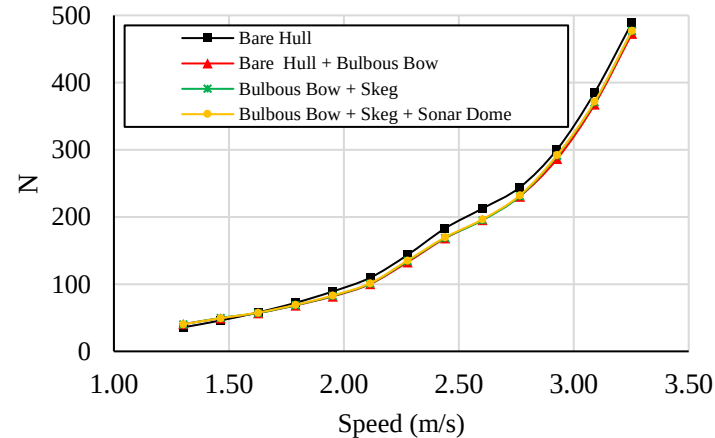


Figure 8 Total resistance vs speed.

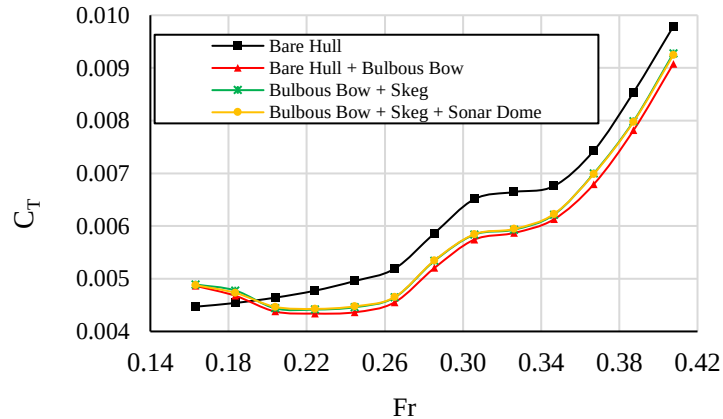


Figure 9 Total resistance coefficient, C_T .

The evaluation of frictional resistance across various hull configurations indicates a consistent increase in total resistance for all appended cases compared to the bare hull as shown in Table 4 and Figure 10. This increase can be attributed primarily to the enlarged wetted surface area introduced by the installation of appendages. Specifically, the bulbous bow alone resulted in an average increase in frictional resistance of 6.09%, while the addition of the skeg further elevated this value to 6.45%. When all three appendages were integrated, the frictional resistance reached an average increase of 6.97%, with the maximum value exceeding 10% at higher Froude numbers ($Fr \geq 0.39$). These findings emphasize critical design consideration: while some appendages may yield substantial reductions in pressure resistance, especially in the transitional speed range, but they also contribute to a rise in frictional resistance. Consequently, a balanced approach is required in appendage design to optimize overall hydrodynamic performance.

The analysis of pressure resistance, presented in Table 5 and Figure 11, reveals that the application of appendages yields a notable reduction in form drag, particularly at moderate to high Froude numbers. While pressure resistance in the bare hull configuration rises significantly with speed, from 8.31 N at $Fr = 0.16$ to 363.64 N at $Fr = 0.41$, the appended configurations consistently demonstrate lower values due to the presence of bulbous bow, indicating improved flow characteristics around the hull.

Table 4 Friction resistance comparison

Friction Resistance (N)									
Fr	V (m/s)	Re	Bare Hull	Bare Hull + Bulbous Bow	Rel. to Bare Hull (%)	Bulbous Bow + Skeg	Rel. to Bare Hull (%)	Bulbous Bow + Skeg + Sonar Dome	Rel. to Bare Hull (%)
0.16	1.30	8.026E+06	27.44	28.75	4.79	28.78	4.90	28.93	5.43
0.18	1.46	9.029E+06	33.83	35.40	4.65	35.12	3.81	35.39	4.61
0.20	1.63	1.003E+07	40.67	42.38	4.21	42.40	4.25	42.51	4.52
0.22	1.79	1.104E+07	48.03	50.00	4.11	50.05	4.22	50.37	4.88
0.24	1.95	1.204E+07	55.70	58.07	4.25	58.38	4.82	58.72	5.42
0.26	2.11	1.304E+07	63.53	66.54	4.73	66.59	4.81	66.84	5.20
0.29	2.28	1.405E+07	71.72	75.69	5.53	75.72	5.57	76.21	6.26
0.31	2.44	1.505E+07	79.58	84.90	6.68	85.01	6.82	85.27	7.15
0.33	2.60	1.605E+07	88.40	95.43	7.95	94.65	7.07	95.13	7.62
0.35	2.77	1.705E+07	96.69	104.57	8.15	104.80	8.39	105.09	8.68
0.37	2.93	1.806E+07	106.17	114.82	8.15	115.54	8.82	116.31	9.54
0.39	3.09	1.906E+07	115.68	124.93	7.99	127.25	10.00	127.82	10.49
0.41	3.25	2.006E+07	125.68	135.71	7.99	138.78	10.43	139.25	10.80
Avg.					6.09		6.45		6.97

Table 5 Pressure resistance comparison

Pressure Resistance (N)									
Fr	V (m/s)	Re	Bare Hull	Bare Hull + Bulbous Bow	Rel. to Bare Hull (%)	Bulbous Bow + Skeg	Rel. to Bare Hull (%)	Bulbous Bow + Skeg + Sonar Dome	Rel. to Bare Hull (%)
0.16	1.30	8.026E+06	8.31	11.81	42.13	11.46	37.90	11.38	36.88
0.18	1.46	9.029E+06	12.13	13.94	14.91	14.62	20.54	14.08	16.13
0.20	1.63	1.003E+07	17.33	14.64	-15.55	14.67	-15.38	15.15	-12.58
0.22	1.79	1.104E+07	24.15	18.38	-23.91	18.62	-22.90	18.79	-22.20
0.24	1.95	1.204E+07	33.51	23.78	-29.03	24.18	-27.86	24.50	-26.89
0.26	2.11	1.304E+07	46.09	33.63	-27.02	34.30	-25.57	34.62	-24.88
0.29	2.28	1.405E+07	71.87	57.13	-20.51	58.76	-18.25	59.05	-17.84
0.31	2.44	1.505E+07	103.45	83.34	-19.44	83.76	-19.03	84.43	-18.39
0.33	2.60	1.605E+07	124.23	100.26	-19.30	100.54	-19.07	101.28	-18.48
0.35	2.77	1.705E+07	147.40	126.06	-14.48	126.09	-14.46	127.21	-13.70
0.37	2.93	1.806E+07	194.61	171.75	-11.75	175.89	-9.62	175.86	-9.63
0.39	3.09	1.906E+07	269.48	242.57	-9.99	243.54	-9.63	243.89	-9.50
0.41	3.25	2.006E+07	363.64	337.23	-7.26	338.24	-6.98	338.08	-7.03
Avg.					-10.86		-10.02		-9.85

The bulbous bow alone offers the greatest contribution to pressure resistance reduction, particularly between $Fr = 0.22$ and $Fr = 0.33$, where reductions of -19% to -29% are observed. The most significant decrease occurs at $Fr = 0.24$, with pressure resistance reduced by 29.03%, from 33.51 N to 23.78 N. When the skeg is added, the overall pressure drag remains lower than that of the bare hull, with the benefit of adding bulbous bow previously. On average, the bulbous bow + skeg configuration results in a 10.02% reduction in pressure resistance across the evaluated speed range. The inclusion of the sonar dome slightly reduces the net benefit but still achieves substantial resistance reduction due to the advantage of bulbous bow, with an average improvement of 9.85% compared to the bare

hull. Notably, even at higher speeds ($Fr \geq 0.39$), the full appendage configuration maintains a consistent pressure resistance decrease of nearly -9.5% , suggesting that the appendage design does not significantly disrupt stern flow at operational velocities. These results affirm the role of appendages in streamlining flow and mitigating adverse pressure gradients along the hull. In particular, the bulbous bow proves highly effective in reducing pressure (wave-making) resistance in the transitional regimes, while the skeg and sonar dome contribute to alter flow alignment and increase separation at the aft body, hence friction resistance.

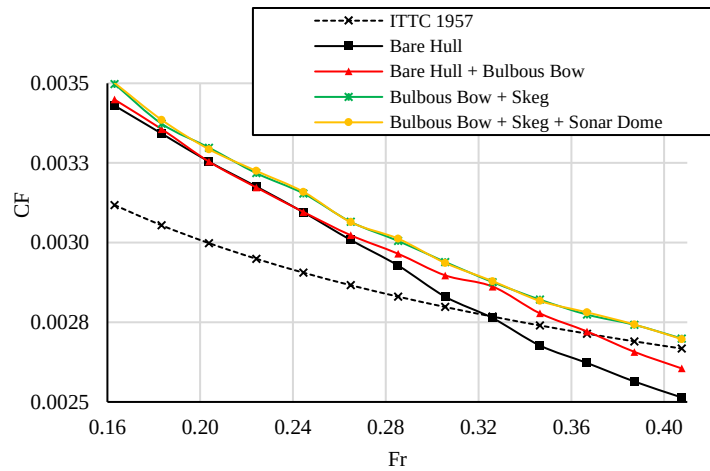


Figure 10 Friction resistance coefficient, C_F

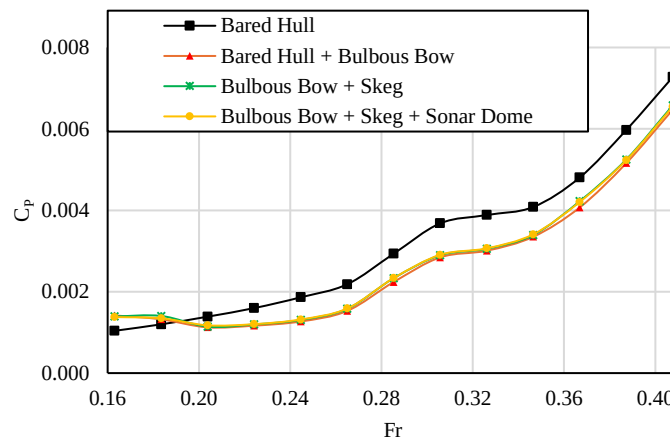


Figure 11 Pressure resistance coefficient, C_P

3.2 Flow visualization

Flow visualization techniques were employed to elucidate the influence of appendages on wake dynamics and pressure distribution. The wave pattern comparison was made only for bare hull and fully appended hull since wave pattern generally driven by waterplane geometry, see Figure 12. In this study, the wave patterns illustrated in Figure 12 correspond to time-averaged solutions obtained from the unsteady RANS-VOF computations. Time averaging was applied after the solution reached a statistically steady state to ensure that the free-surface visualization reflects stable hydrodynamic behavior rather than instantaneous fluctuations. Wave pattern around the bare hull reveals distinct divergent and transverse wave components, especially pronounced near the stern. This indicates stronger wave-making resistance, as the abrupt geometry at the transom and lack of flow control surfaces allow high-pressure zones to develop and dissipate energy inefficiently. The visible crest height and wavelength suggest a significant amount of energy is being radiated away in the form of surface disturbances.

In contrast, the fully appended configuration generates a noticeably smoother wave profile with dampened amplitudes, particularly in the stern region. The tapering effect from the bulbous bow and flow-conditioning properties of the skeg and sonar dome promote a more favorable pressure gradient, delaying flow separation and reducing wave steepness. The smoother wave patterns seen in the appended hull indicate a reduction in wave-making resistance primarily due to enhanced pressure distribution and minimized abrupt flow transitions. This supports the optimization objective in hull design, which is especially for displacement vessels, to streamline aft-end flow and minimize free-surface disruptions.

The velocity contour is presented in Figure 13. The bare hull streamlines plot shows steep gradients near the hull boundary, particularly at the fore and aft ends. The absence of bow flow modification devices results in strong acceleration zones forward and sharp flow separation at the stern. This discontinuity in flow field confirms the generation of vortices and increased form drag due to pressure imbalance, in agreement with RANS-based turbulence models where flow separation causes high viscous dissipation.

Introducing the bulbous bow leads to a more uniform inflow along the mid-body. The streamlined bow shape redistributes flow vectors in a manner that reduces the bow wave formation and enhancing laminar stability. The observed effect corresponds with the

classic design principle that bulbous bows interact constructively with the primary bow wave system, leading to wave cancellation and energy savings.

The addition of a skeg refines flow direction under the hull and stabilizes the stern wake. The velocity profile becomes smoother in the aft section, suggesting that the skeg acts as a flow guide, reducing crossflow and secondary vortices. This is consistent with known benefits of skegs in reducing yaw-induced flow divergence and enhancing propulsion efficiency.

With all appendages in place, the velocity streamlines are the most coherent and continuous across the hull length. Flow acceleration is controlled, boundary layer growth is gradual, and there is minimal evidence of separation at the stern. This yields an ideal velocity gradient, reducing form drag and improving wake uniformity, which benefits both propulsive performance and cavitation resistance.

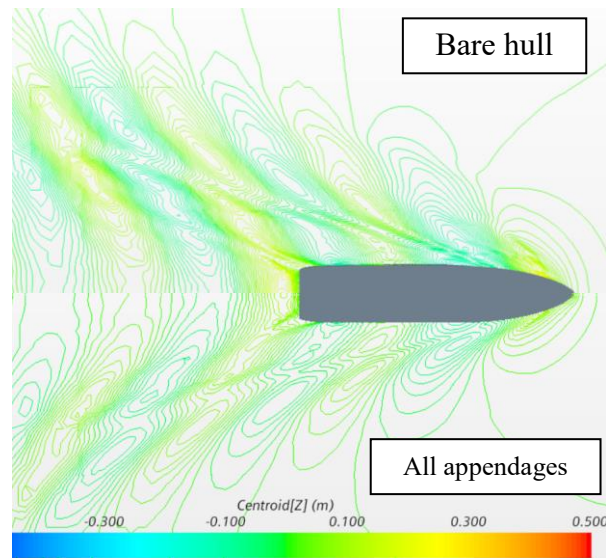


Figure 12 Comparison of free-surface wave patterns between the bare hull and fully appended configuration.

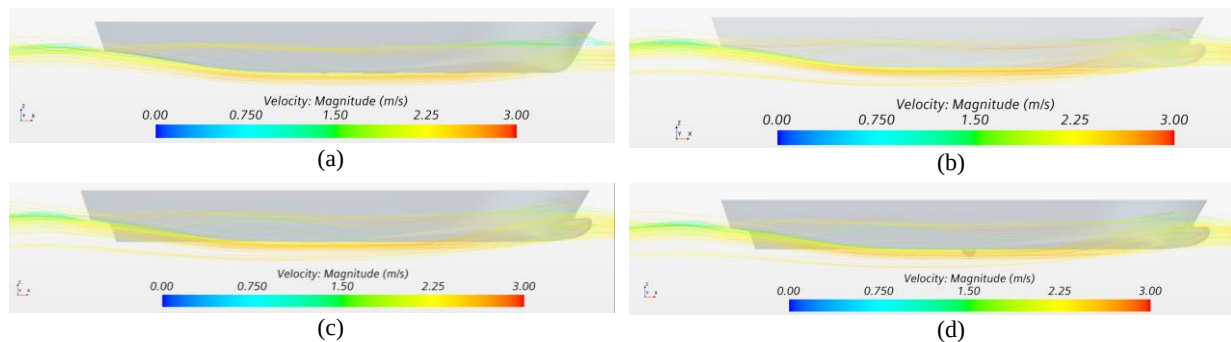


Figure 13 Streamline visualizations around the stern region for each appendage configuration, illustrating differences in wake structure and flow alignment a) bare hull, b) bare hull with bulbous bow, c) bulbous bow with skeg and d) all appendages – bare hull with bulbous bow, skeg and sonar dome.

3.3 Pressure distribution

The comparative analysis of pressure distribution across the four hull configurations, presented in Figures 14 – 16, reveals distinct differences in hydrodynamic performance. The bare hull configuration (a) exhibits high stagnation pressure at the bow and pronounced low-pressure zones at the stern, particularly along the hull surface and bottom. These characteristics reflect inefficient pressure recovery and significant flow separation, resulting in increased form drag and unsteady wake behavior.

In contrast, the inclusion of a bulbous bow (configuration b) effectively reduces the peak pressure at the bow and smoothens the pressure gradient along the hull. This modification not only decreases wave-making resistance but also improves pressure distribution in the forward section of the vessel, contributing to more stable inflow conditions.

Adding a skeg to the bulbous bow (configuration c) primarily enhances the stern flow behavior. The pressure distribution indicates better recovery in the aft region, with less severe low-pressure areas and more balanced flow around the bottom surface. Although the frontal pressure profile remains similar to configuration b), the skeg contributes significantly to wake alignment and crossflow suppression, which are critical for propulsive efficiency.

The fully appended hull (configuration d) demonstrates the most uniform and favorable pressure distribution among all configurations. The bow region exhibits minimized stagnation pressure, while the stern maintains moderate positive pressure, indicating well-managed inflow and outflow characteristics. The sonar dome, in particular, aids in maintaining pressure continuity beneath the hull and conditioning the flow into the propeller plane. Overall, the combination of appendages yields optimal hydrodynamic behavior by minimizing abrupt pressure transitions, reducing flow separation, but enhancing total resistance characteristics.

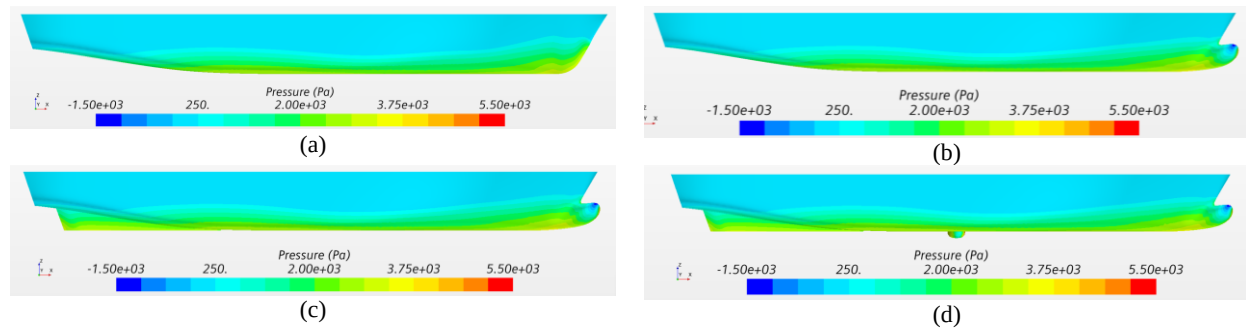


Figure 14 Pressure distribution on hull surface a) bare hull, b) bare hull with bulbous bow, c) bulbous bow with skeg and d) all appendages – bare hull with bulbous bow, skeg and sonar dome.

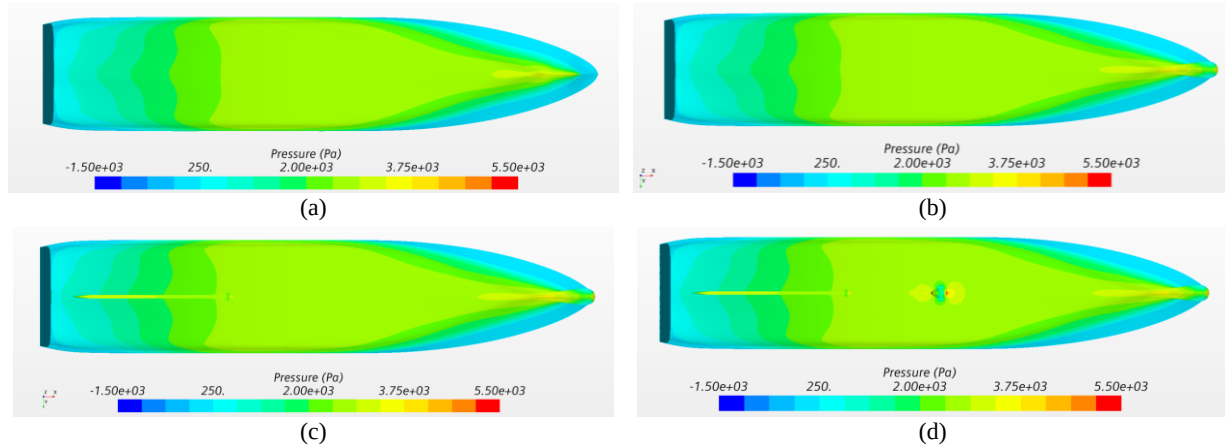


Figure 15 Bottom pressure distribution for various appendage configurations, indicating pressure concentration zones a) bare hull, b) bare hull with bulbous bow, c) bulbous bow with skeg and d) all appendages – bare hull with bulbous bow, skeg and sonar dome.

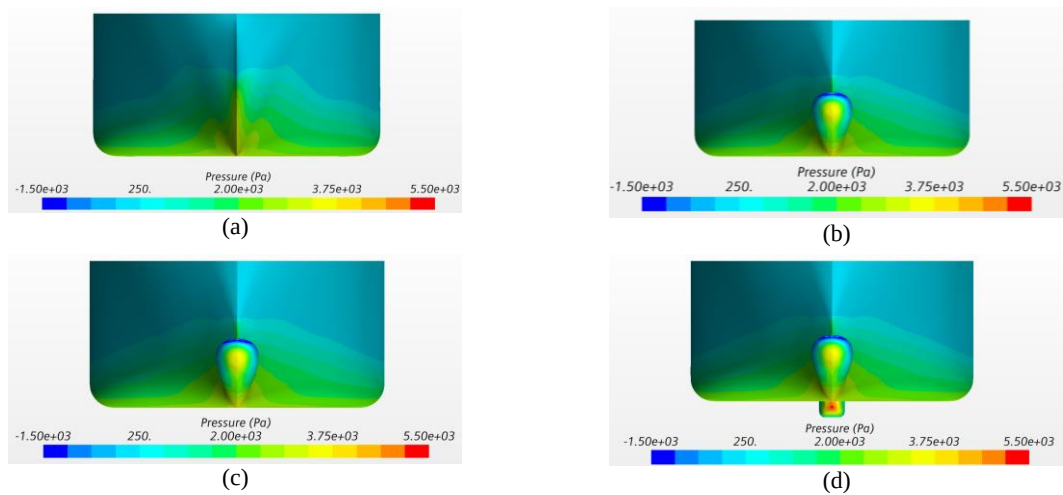


Figure 16 Frontal pressure distribution a) bare hull, b) bare hull with bulbous bow, c) bulbous bow with skeg and d) all appendages.

4. Discussion

In contrast to those studies mentioned in introduction section, the present work introduces a stepwise evaluation method in which each appendage including bulbous bow, skeg, and sonar dome, is analyzed cumulatively under controlled numerical conditions. This modular breakdown enables a clearer understanding of how each component contributes to overall resistance trends. The outcomes not only reinforce earlier conclusions on appendage-induced drag [36, 37] but also provide practical guidelines for incremental appendage integration during the early design phase.

The resistance characteristics of the displacement hull under different appendage configurations were analyzed in terms of total resistance, frictional resistance, and pressure resistance. Each component exhibited distinct trends across the studied Froude number range ($Fr = 0.16$ to 0.41), reflecting the interplay between hydrodynamic benefits and geometric penalties introduced by the added structures. Although this study is purely numerical in nature, a detailed grid convergence study was conducted to ensure solution accuracy and stability. The mesh sensitivity analysis showed that resistance predictions varied by less than 1% across the final refinement levels, providing confidence in the numerical reliability of the results.

4.1 Total resistance

The analysis of total resistance indicates that the integration of appendages can lead to measurable performance improvements under specific conditions. The bulbous bow alone proved most effective in reducing total resistance, particularly within the transitional speed range ($Fr = 0.24\text{--}0.31$), achieving a maximum reduction of -8.62% at $Fr = 0.26$. The addition of a skeg further improved aft-body flow behavior, yielding comparable reductions up to -8.21% . Although the sonar dome added some resistance at lower speeds, its overall impact was minor. The fully appended configuration produced an average reduction in total resistance of 2.53% , affirming the cumulative benefit of a well-integrated appendage system.

4.2 Frictional resistance

Frictional resistance consistently increased across all appended configurations. This is a direct consequence of the increased wetted surface area, which amplifies viscous drag. The bulbous bow alone raised frictional resistance by an average of 6.09% , and the inclusion of the skeg elevated it further to 6.45% . The most pronounced increase was observed in the full configuration, which averaged 6.97% , with peak values exceeding 10% at $Fr \geq 0.39$. These findings highlight the trade-off between form improvement and surface area expansion, particularly at higher speeds where pressure effects become more dominant.

4.3 Pressure resistance

The pressure resistance component, often linked to flow separation and pressure recovery, demonstrated the clearest benefits from appendage design. The bulbous bow led to substantial reductions in pressure drag up to -29.03% at $Fr = 0.24$. This results in altering wave patterns and reducing flow deceleration around the bow region. The skeg improved aft-body flow reattachment, maintaining an average reduction of 10.02% when combined with the bulbous bow. The addition of the sonar dome slightly reduced the overall gain but still resulted in a 9.85% average pressure drag reduction relative to the bare hull.

In addition, the relatively low C_p values observed around the forward appendages can be explained by the strong flow-acceleration mechanism induced by the curvature of the bulbous bow and the underside of the sonar dome. These geometrically convex regions promote localized velocity increase, resulting in pressure depression consistent with Bernoulli-driven behavior. Similar patterns of reduced pressure coefficients around streamlined protrusions were reported by Zhang et al. [38], who demonstrated that pressure minima form naturally in areas of intensified flow curvature around domes and forebody appendages. Majumdar et al. [39] also documented comparable low- C_p zones in sonar dome studies, attributing them to accelerated flow and improved pressure recovery along the hull. The present results therefore align well with established hydrodynamic evidence, confirming that the lower C_p values arise from fundamental flow-curvature interactions rather than numerical artifacts.

Furthermore, the normalized friction and pressure coefficients shown in Figures 10 and 11 provide additional insight into the underlying hydrodynamic mechanisms. The monotonic increase in C_F across all configurations reflects the dominant role of wetted-surface expansion caused by the appendages, consistent across the entire Froude number range. In contrast, the normalized C_P values clearly highlight the effectiveness of the bulbous bow in reducing form drag within the transitional regime, where wave-interference effects are strongest. These normalized trends align with earlier CFD findings for streamlined forebody and dome geometries, which similarly report reduced pressure coefficients and improved flow alignment in the presence of well-integrated appendages. The consistency between these normalized values and established literature supports the physical plausibility of the present results.

Despite the strengths of the stepwise evaluation approach, several limitations should be acknowledged. First, the study is entirely numerical, and the absence of towing-tank or benchmark experimental data prevents direct physical validation of the computed resistance components. Second, the use of a RANS-VOF framework introduces modeling assumptions that may influence predictions of flow separation and free-surface interactions. Third, propeller-appendage interaction effects, which can significantly influence stern-region hydrodynamics, were not included and remain an important area for future investigation. These limitations clarify the scope of the present findings and outline directions for future work aimed at strengthening the overall validation framework.

5. Conclusion

Unlike many previous studies that evaluated individual appendage types in isolation, this work systematically investigates the cumulative and comparative effects of multiple appendages, which are bulbous bow, skeg, and sonar dome, under identical numerical conditions. This approach enables a clear quantification of resistance trade-offs and provides deeper insights into integrated appendage design. Computational Fluid Dynamics (CFD) simulations were performed using the Reynolds-Averaged Navier-Stokes (RANS) equations coupled with a Volume of Fluid (VOF) method to account for free-surface interactions. The analysis covered a wide range of Froude numbers ($Fr = 0.16$ to 0.41), allowing detailed assessment of resistance behavior under varying speed conditions.

Four configurations were assessed including bare hull (as a reference), bare hull with bulbous bow, with bulbous bow and skeg, and with the full set of appendages including the sonar dome. Each configuration was assessed in terms of total resistance, as well as its frictional and pressure components. A grid refinement study was also conducted to ensure mesh independence and solution reliability.

The results revealed that the bulbous bow provided the most substantial reduction in total resistance, which is up to 8.62% , particularly within the transitional Froude number range ($Fr = 0.24\text{--}0.31$). The addition of a skeg improved flow coherence in the stern region and helped sustain form drag reductions. While the sonar dome introduced a slight increase in frictional resistance, it maintained favorable performance at higher speeds. Overall, the fully appended configuration achieved an average total resistance reduction of 2.53% compared to the bare hull.

Frictional resistance increased in all appended cases due to the enlargement of wetted surface area, with the full configuration showing an average increase of 6.97% . However, these increases were largely offset by the significant reduction in pressure resistance, particularly for the bulbous bow, which achieved a maximum form drag reduction of 29.03% .

Although the appendages demonstrated clear benefits at transitional and higher Froude numbers, it is important to note that they also introduce a measurable penalty at low speeds. As shown in Table 3, the fully appended configuration yields increased total resistance at $Fr = 0.16$ due to the dominance of frictional forces and the limited influence of wave-interference mechanisms at such

low velocities. This low-speed performance drawback should therefore be considered in practical applications, particularly for vessels that frequently operate in harbor or maneuvering conditions. Nonetheless, the improvements observed at service and cruising speeds indicate that the overall hydrodynamic impact remains favorable within the intended operational envelope.

The novelty of this research lies in its detailed decomposition of resistance components for combined appendage configurations. Most notably, the study provides a clear quantification of the trade-off between frictional and pressure resistance, offering practical design insights for naval architects. The identification of the transitional Froude number window as optimal for bulbous bow application in displacement ship, along with the inclusion of sonar dome effects from a hydrodynamic viewpoint, by demonstrating how specific appendage combinations alter resistance profiles under varying flow regimes.

It should also be noted that all findings presented in this study are derived solely from numerical simulations without experimental validation. Consequently, the quantitative values, such as the maximum resistance reduction of -8.62% observed for the bulbous bow configuration, reflect the behavior of the present computational model and should be interpreted within the limitations of RANS–VOF predictions. While the mesh-independence assessment ensures internal consistency, physical validation through towing-tank experiments or full-scale measurements would be required to further verify the accuracy and generality of these results.

This systematic approach enables designers to optimize appendage selection during early-stage hull form refinement, particularly for vessels operating in transitional Froude regimes. Future studies may expand on these findings by incorporating other appendage types and propulsor interaction or experimental validation.

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