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Parametric studies on bulbous bow to reduce the bow-induced vortices for a naval vessel

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ABSTRACT

The hydrodynamic optimization of a bulbous bow for naval vessels presents various challenges to the industries and scientific communities, considering aspects like reducing resistance and noise. In the context of sustainable shipping and current Energy Efficiency Design Index (EEDI) requirements, merchant vessels are seeking an optimized bulbous bow that offers improved resistance characteristics, thereby ensuring compliance with statutory emissions requirements. On the other hand, naval vessels, especially those equipped with sonar equipment in their bulbous bows (commonly known as sonar domes), often face issues related to noise which interfere with sonar operations, potentially affecting the vessel's stealth signature. Equally important but less discussed is the phenomenon of vortex shedding from the bow, where the shape of the bulbous bow leads to vortex shedding which interferes with the propeller. The bow-induced vortices can decrease propeller efficiency, induce premature cavitation, and increase propeller noise, which is a significant concern both stealth of the vessel and environmentally. In the current study, an ITTC benchmarking model was considered for resistance validation, which indicated a 1 % to 6 % deviation from experimental results for the viscous resistance component of the vessel. After validation, the analysis was carried out for variations in bulbous bows using the Free-Form Deformation (FFD) method using CAESES. A total of twenty-five variations of the bulbous bows were simulated at Froude number of 0.248 and 0.45 to study the effect of the bulb vortex on the propeller wake. This indicated that while the curvature and slope of the bulb at the top and bottom parts can control the strength of the bow vortex generated but may not significantly reduce the wake fraction of the vessel.

Keywords: bow-induced vortices, CFD, free-form deformation (FFD), nominal wake faction.

1. Introduction

Ships have been fitted with bulbous bows, initially designed to reduce wave-making resistance through the concept of destructive wave interference. This design typically involves adding a protrusion to the hull at the forward section, below the waterline, near the forward perpendicular. Such a configuration generates a wave system that is out of phase with the bow wave, thereby effectively reducing wave-making resistance. Over time, the application of bulbous bows has extended to various types of vessels, especially those with higher block coefficients. The goal in such cases is to lessen viscous resistance, as seen in larger vessels like bulkers and tankers, and sometimes to minimize motion in vessels like dredgers by adding mass to the forward section.

In naval vessels, however, the design requirements for bulbous bows become more complex due to dual operating speeds, and the need for stealth and efficient speed requirements. Typically, the bulbous bow region is used to house a hull-mounted sonar dome, which comes with its own set of operational demands. Researchers have studied the impacts of the bulbous bow on reducing overall vessel resistance and noise. The unique shape of the bulbous bow, extending below the baseline, introduces an additional challenge in the form of bulbous bow generated vortex. This vortex, originating from the hull-mounted sonar dome i.e. bulbous bow, travels beneath the hull and can potentially reach the propeller area. Understanding and addressing this phenomenon is vital for the effective and efficient operation of naval vessels.

[1] emphasized the importance of vibro-acoustic characteristics, noting the need to consider factors such as structural arrangement, materials, the size of the dome etc. They proposed that full-scale experiments might be required for a comprehensive understanding of these phenomena, especially when striving to achieve the desired vibro-acoustic characteristics of the sonar dome. Further, [2] discussed hull-mounted sonars, which generally project below the ship's keel. He noted that local flow-induced vibrations at the bulb could increase sonar self-noise with speed, a finding supported by experimental data. On the other hand, [3] suggested that simply enhancing the structural strength of the sonar dome and adding a sound-absorbing layer to its backing might be a more straightforward approach than analyzing the hydrodynamic behaviour of the bulb. Some studies [4] have indicated that changes in the length of the bulb may result in up to a 17 % reduction in resistance.

In conditions where bulb-generated vortices occur, hydrodynamic analysis becomes crucial in the design process. This importance is due to the possibility of bulb vortices reaching the propeller plane, potentially affecting its

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operation and, consequently, impacting the vibro-acoustic characteristics of the system. Therefore, assessing the bulb vortex is a critical factor in the initial design phase.

Naval hull forms are mission-oriented and come equipped with a plethora of appendages to accomplish various tasks during a single voyage. However, the influence of these appendages, especially domes, can drastically affect the vessel's performance due to the vortices they create. These vortices travel downstream to the propeller plane, potentially interfering with propeller performance and significantly contributing to increased hull resistance and propeller operation issues.

This study was initiated with the objective of parametrically altering one of the main appendages, the hull-mounted sonar dome, which acts as a bulbous bow. The focus was on studying the dome vortices, their travel distance, and their effect on the propeller for a given bulb configuration without appendages. The final step involved selecting an improved bow shape by optimizing within the chosen design space. This included checking the propeller's nominal wake fraction as a performance indicator to conclude the most effective sonar dome configuration using computational tools.

2. Materials and methods

2.1. Model data

For analysing bulb vortex generation, the reference vessel was selected from the ITTC benchmarking model, DTMB 5415. The hull surface data was sourced from [5], which provides a suitable Navy Combatant hull design, including a hull-mounted sonar dome as depicted in the Figure 1. The dimensions of the hull are detailed in Table 1.

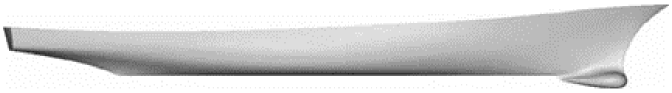


Figure 1. Hull form of DTMB 5415.

Table 1. Geometrical data for INSEAN model 2340 and full-scale ship.

Dimensions	Unit	Ship	Model
Scale factor	λ	-	24.824
Length between perpendiculars	LPP (m)	142	5.72
Length at water level	LWL (m)	142	5.72
Breadth	B (m)	18.9	0.76
Draft	T (m)	6.16	0.248
Trim angle	(deg)	0	0
Displacement	Δ (t)	8636	0.549
Volume	▽ (m^3)	8425.4	0.549
Wetted surface	S_W (m^2)	2949.5	4.786

The DTMB and INSEAN models, which are geometrically similar, are well documented in the literature. Since experimental data [6] for the INSEAN model is readily available, the corresponding dimensions are presented in Table 1, and initial validation was considered using this INSEAN experimental data.

2.2. Numerical method

The simulations are carried out using the commercially available software SHIPFLOW, which is utilized for CFD analysis in this study. The analysis primarily adopts two approaches: the first calculates total resistance as two components, one being the wave-making resistance, which employs Free Surface Potential Flow calculations through a potential flow solver, and the other being the viscous components, calculated using a RANSE solver with a global approach and the EASM Turbulence model.

The second approach involves the Volume of Fluid (VOF) for viscous free surface modelling, where the free surface is captured during RANS computation using the k-w SST Turbulence model.

Generally, the free surface potential flow approximation is less accurate at higher Froude numbers. Thus, when higher Froude numbers with waves need to be calculated, VOF simulation becomes a preferable choice despite its longer simulation time.

2.3. Parametric variation on bulb

To achieve different bulb configurations, the CAESES software's default FFD option is employed. This allows for local modifications of existing geometries to generate multiple variations on the desired configuration, generally considered as partial parametric modeling. In this study, modifications to the hull surface are not made directly but are instead imposed on the offset points, which serve as input for the CFD tool SHIPFLOW. The details and locations of these offset points are illustrated in Figure 2.

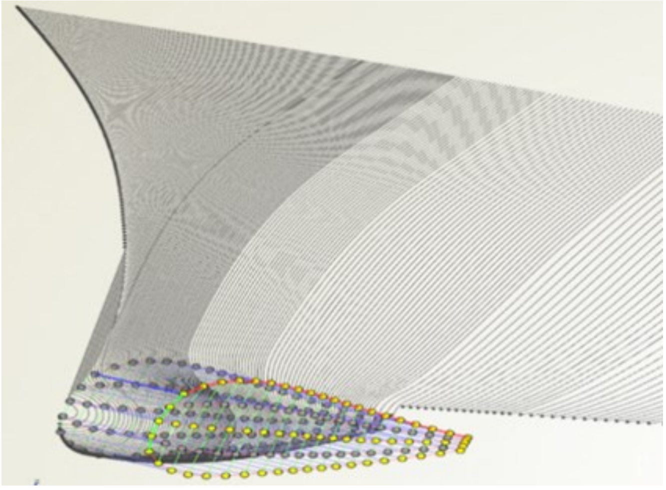


Figure 2. Offsets in the bow region on the hull form with the FFD bounding box.

Figure 2 shows that, instead of using a conventional rectangular FFD box, the box is modified to match the bulb shape that surrounds the geometry for this particular case. To ensure that the starting points of the sections always remain on the central plane, the box's continuities are defined by fixing some control vertices, thus maintaining a constant profile. This approach prevents any openings in the hull that could cause problems during later simulation stages. Once the profile is fixed, variations in the bulb are achieved by selecting from a set of operations that affect the bulb's breadth in the transverse direction, applied to the geometry within the deformation box.

The transverse operations controlling the local breadth are defined by the terms "up" and "do," as indicated in Figure 3. "Up" refers to the set of points controlling the curvature of the bulb's top, while "do" controls the curvature of the bottom. The rest are kept constant, as shown in Figure 2. The parameters of the up and down points vary from -0.5 m to 0.5 m in steps of 0.25 m, resulting in a total of twenty-five bulb variations. Each bulb design is named sequentially from Dbulb00 to Dbulb24.

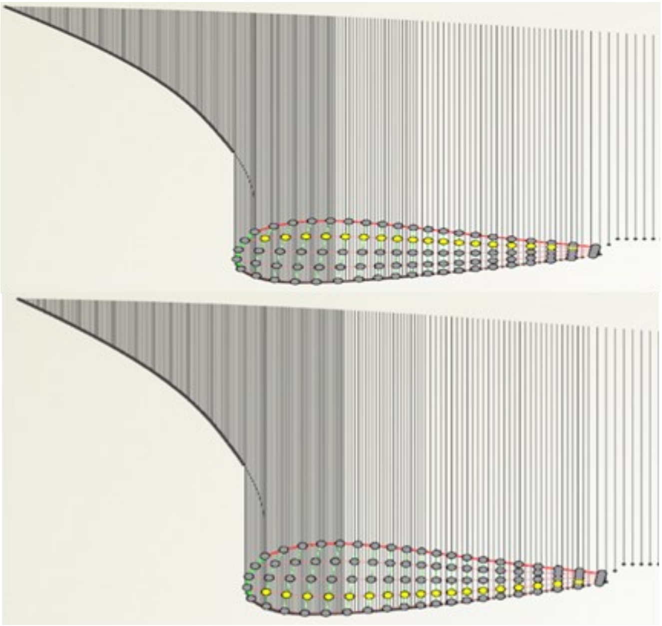


Figure 3. The definition of"up" & "do" on the FFD box (hilted point indicate the corresponding region on modification).

2.4. Methodology

The comprehensive methodology encompasses an initial estimation of resistance for a range of speeds, from Froude numbers of 0.08 to around 0.45, followed by validation with experimental results. Once validation is achieved, design cases for various bulbous bow variations are generated, which are then utilized in analyzing the flow around the bulb. For generating these design variations, the FFD method in CAESES is employed. Given the focus on capturing specific flow characteristics for different designs, local refinements are applied to ensure accurate capture of vortices around the hull. Ultimately, the optimal bow configuration is determined by eliminating designs that exhibit the maximum total wake variation on the propeller plane.

3. Results and discussion

The DTMB 5415 vessel, features a large bulbous bow, as to house the sonar equipment. Before analyzing the final bulb shape an initial CFD model validation conducted. The simulations estimated resistance as two main components one residuary resistance and other frictional resistance. The residuary resistance is primarily calculated using a potential flow solver, whereas viscous resistance is determined through RANS-based simulation.

The initial resistance simulations, conducted with a Vcoarse mesh of 0.69 million cells across various speeds, compared experimental and simulated results, as depicted in Figure 4. These results show good convergence at lower Froude numbers, with discrepancies increasing to around 25 % at higher Froude numbers, a common trend as Froude number rises. For a more accurate comparison of the viscous resistance component, the results are compared with experimental data, indicating a maximum deviation of 6 % for experimental results, as indicated in the Figure 5.

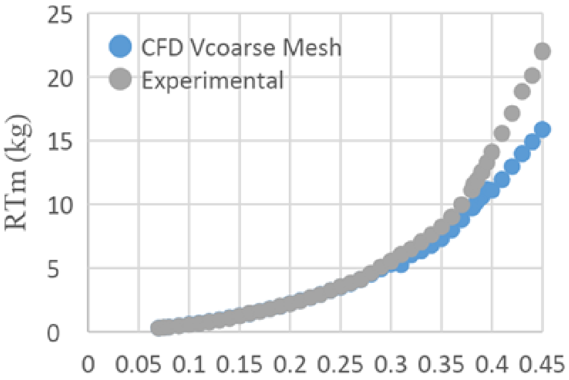


Figure 4. Comparison of experimental and CFD results for total resistance.

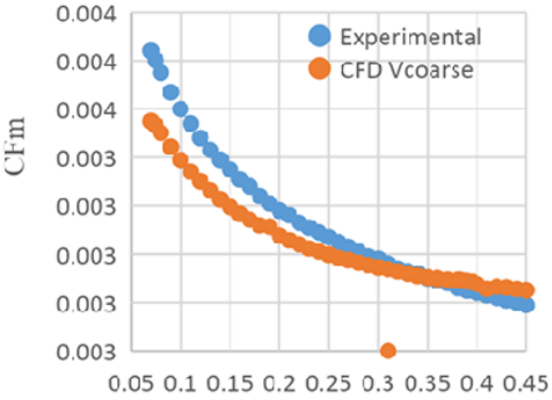


Figure 5. Comparison of experimental and CFD results for coefficient of frictional resistance.

Since this study focuses more on the viscous component generated by the bulb, the model is applied across different speed ranges to analyze the viscous resistance of various bulb designs. However, to assess total resistance accurately, the CFD model's second approach, the VOF method, is employed. This full viscous flow solver simulation estimates two-phase flow. For this analysis Froude number 0.45 speeds is considered where deviations from experimental results are significant. To ensure systematic analysis at this speed, cases are simulated to estimate total resistance under two conditions, one where the vessel is fixed (not free to sink or trim) and the other allowing for sink and trim. The results are present in Table 2 and wave elevation, velocity contours at the propeller plane for both cases are presented in Figures 6 and 7.

Table 2. Experiment and VOF case of CFD results at different conditions.

	Case 1		Case 2
Fn	0.45	0.45	0.45
R_{Tm} _Exp (kg)	21.95	21.95	21.95
R_{Tm} _CFD (Kg)	18.34	17.87	21.34
% error	16.4	18.6	2.8
Sinkage /Trim	No	No	Yes
No of cells in million	1.55	4.25	4.25

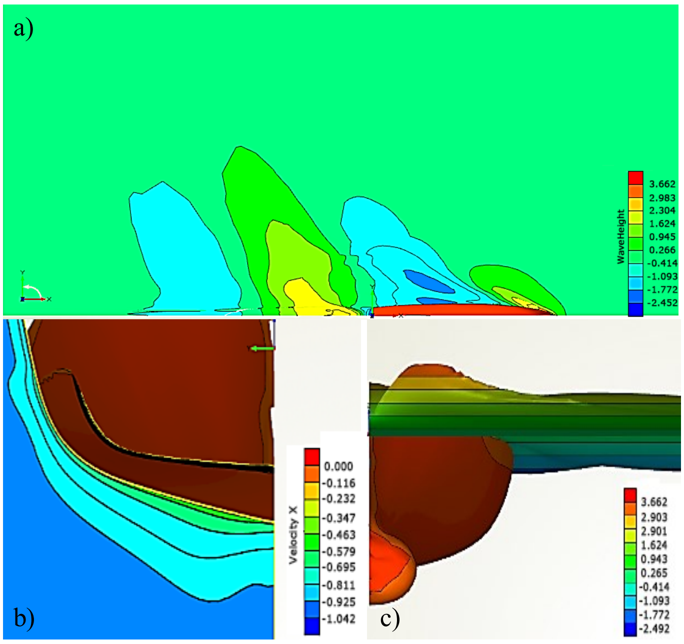


Figure 6. Case 1 with 4.25 million cells, a) wave elevation plan view, b) wave elevation body plan view, c) velocity at the near to the propeller plane.

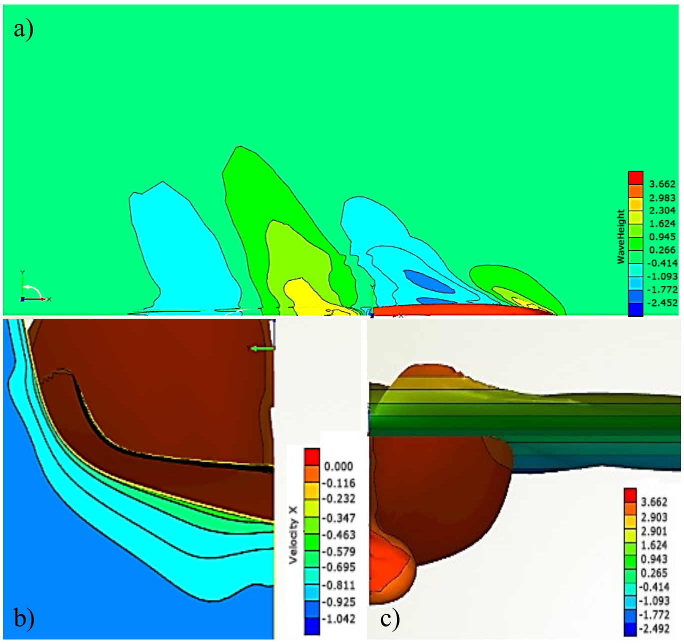


Figure 7. Case 2 a) wave elevation plan view, b) wave elevation body plan view, c) velocity at the near to the propeller plane.

In conducting a parametric study of various bulb configurations, Dbulb00 to Dbulb24 bulb designs are considered. To ensure that the vortex generated by the bulb was accurately captured. Local requirements, which start from the bulb region and end at the aft end of the vessel, were provided. This configuration, with its refinement, was analysed at two speeds, corresponding to Froude numbers of 0.248 and 0.413. For the Froude number 0.248, two mesh sizes were considered one as 4.16 million (Vcoarse mesh) and 19.61 million (Fine mesh). For Froude number 0.45, only one mesh size of 4.16 million (Vcoarse mesh) was analysed. The analysis of all bulb variations with different grid sizes is presented in Figures 8, 9, and 10 where comparisons are based on different designs and the maximum total wake variation at the propeller plane.

Upon analysing Figures 8 to 10, it becomes evident that exhibits the least total wake variation at the propeller plane, indicating a reduction in bulb vortex strength by the time it reaches this plane. The design that led to the least variation was observed to have minimal upper and lower.

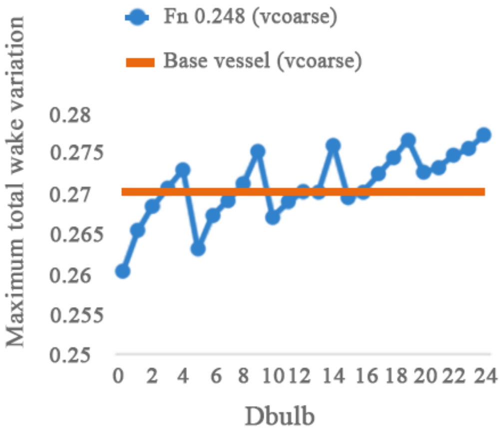


Figure 8. Trend indicating different bulb configurations vs. maximum total wake variation for a Fn 0.248 with 4.16 million cells (Vcoarse mesh).

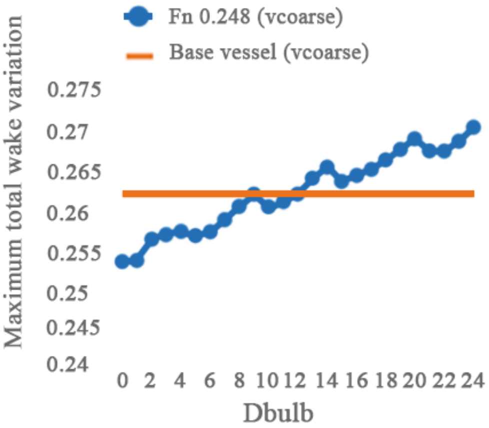


Figure 9. Trend indicating different bulb configurations vs. maximum total wake variation for a Fn 0.248 with 19.61 million cells (Fine mesh).

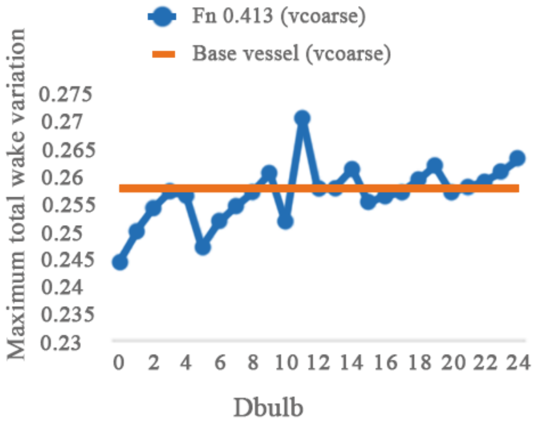
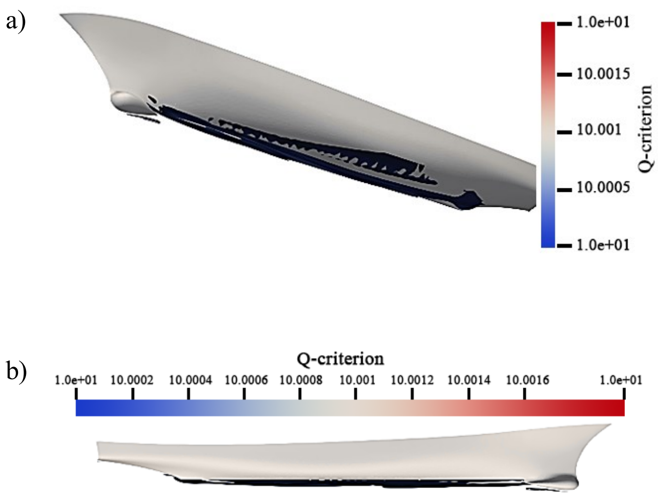


Figure 10. Graph indicating different bulb configurations vs. maximum total wake variation for a Fn 0.413 with 4.16 million cells (Fine mesh).

Variations of the bulb, specifically at -0.5 m 'up' and -0.5 m 'do', as indicated by the movement of points highlighted in Figure 3. This movement of the local bulb section breadth at these two levels is a reduction from the original bulb shape, leading to decreased slopes of the sections in the bulb region at the top and bottom, resulting in a reduced bulb vortex. To analyse this phenomenon with greater clarity, a Q-criterion is employed. This criterion defines vortices as specific areas. The results are plotted and illustrated in Figure 11. These findings are then compared with those of Dbulb 14, which exhibits higher vortex intensities. From Figures 11 and 12, it is noticeable that a distinct bulb vortex appears from the end of the bulb below the baseline and gets aligned with the propeller plane. Additionally, a weaker vortex near the bilge region is observed. When comparing the travel distance of the bulb vortex, it is evident that the bulb design Dbulb00 exhibits a shorter vortex travel distance compared to Dbulb14, as clearly shown when comparing Figures 11(b) with 12(b). This effect of the bulb vortex is also visible in the wake fraction plots of the two designs, illustrated in Figures 11(d) and 12(d). These observations indicate that the bulb significantly impacts naval vessels with hull-mounted sonar domes. Assessing and modifying the bulb can aid in reducing the vortex generated by the bulb.



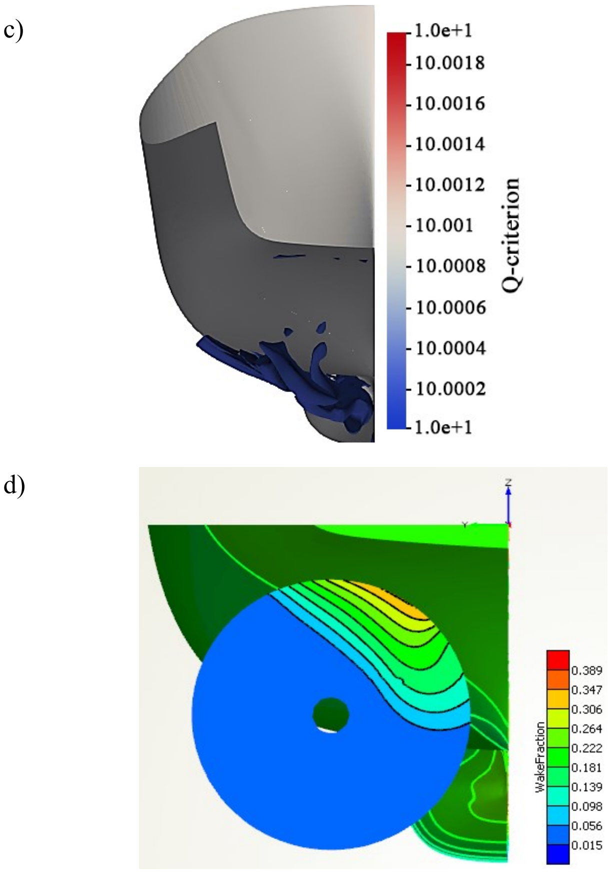


Figure 11. Outputs of Dbulb00 with Q-criterion, (a) perspective view, (b) profile, (c) section view looking from aft, (d) propeller wake fraction.

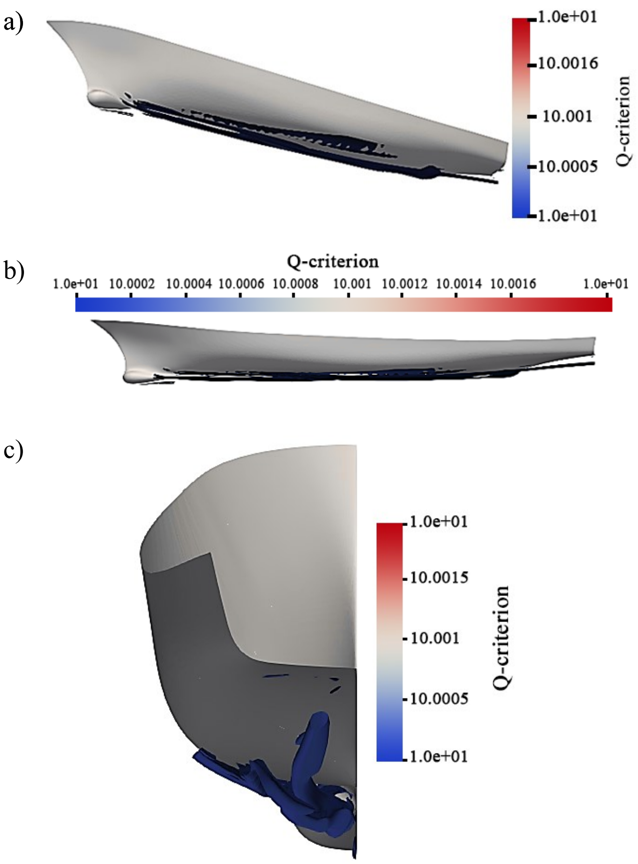


Figure 12. Outputs of Dbulb14 with Q-criterion, (a) perspective view, (b) profile, (c) section view looking from aft, (d) propeller wake fraction.

4. Conclusions

From the detailed simulations, we can draw the following conclusions regarding the implementation of a simulation-based design approach for addressing specific issues in the current context of hull-mounted sonar:

For resistance simulations, the volume of fluid method proves to be more effective in accurately estimating the vessel's resistance. Additionally, it is observed that simulating sinkage and trim, rather than using a fixed body assumption, significantly reduces the deviation in the results in comparison with the published experimental ones. In scenarios with higher than Froude number 0.45, the deviation from experimental results was approximately 2.7 %. However, this increased accuracy comes at the cost of substantially longer simulation times, primarily due to higher mesh size requirements.

Simulations under various bulb design cases demonstrate that changes in breadth dimensions significantly impact the extent of the bulb vortex. Specifically, reducing the breadth at locations above and below the bulb's midpoint can effectively lessen the vortex. This finding is crucial for the initial design phase of similar types of vessels.

In terms of design modifications for the bulb, changes in breadth at two points around the middle of the bulb were considered. While this approach does not provide a comprehensive view of the flow field around the bulb, it serves as an indicative method, suggesting how modifications to the bulb vortex can impact overall design considerations. However, it is also crucial to study other parameters affecting the bulb, such as its length and the waterline slope at the bow.

These insights emphasize the importance of simulation-based design approaches in naval architecture, particularly for hull-mounted sonar applications. They highlight specific areas where such methods can be effectively applied, offering guidance in exploring new facets of design previously unexplored and unexamined.

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