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A Comprehensive Review of Geometric Influences of the Bulbous Bow on the Resistance of the KRISO Container Ship

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Abstract: The hydrodynamic resistance of container ships, especially at medium to high speeds, is greatly influenced by the bulbous bow, an essential design element. The KRISO Container Ship (KCS) has been widely used as a benchmark model because of its well-documented geometry and validated experimental data. A brief overview of the literature on the geometric effects and optimization of bulbous bows for KCS-type vessels is provided in this work. A comparative analysis is conducted among empirical prediction methods, CFD simulations, and experimental tests. Important geometrical factors are analyzed in relation to total and wave-making resistance, including bulb length, width, tip height, and volume ratio. The findings show that coordinated multi-parameter optimization, as opposed to discrete geometric adjustments, is necessary for efficient resistance reduction. A move toward integrated, data-driven, and multi-objective design techniques for energy-efficient bulbous bow development is reflected in recent developments in AI-assisted design, parametric modeling, and surrogate-based optimization.

Keywords: Bulbous bow, CFD simulation, Geometric parameters, Hydrodynamic resistance, KCS container ship.

1. INTRODUCTION

The advancement of numerical hydrodynamic optimization has been greatly aided by benchmark vessels, which offer standardized geometries and verified experimental datasets for comparison. Traditional CFD-based resistance evaluation has gradually given way to integrated, multi-parameter design approaches in research on hull shape and bulbous bow optimization. Numerical hull form optimization employing shape optimization frameworks based on CFD was made possible by early research [1]. Specifically for benchmark vessels like the KCS, further research focused on scenario-based and operating condition dependent optimization shown the sensitivity of resistance performance to trim, draught, and sea states [2,3]. Later research focused on practical design applications, such as bulbous bow refinement for high speed craft, fishing vessels, offshore patrol vessels, and container ships [4-7]. These studies, which included resistance prediction in both calm and wave conditions, trim optimization, and parametric geometry change, emphasized the combined effects of hull shape, operating profile, and free-surface interaction [8-10]. Along with improving validation through the use of combined EFD-CFD approaches, current research has gradually addressed surface condition and environmental concerns, including heterogeneous flow impacts and hull roughness [11,12]. Dihedral and dimensionally optimized bulbous bows are two examples of more specific geometrical concepts that have been studied to lower resistance in small and inland boats [13-15]. Recent research indicates a clear shift toward data-driven and hybrid optimization strategies that combine advanced CFD, weak-scatterer formulations, and machine learning techniques to reduce total and added resistance under realistic operating conditions [16-18]. Despite these advances, there are still problems finding a balance between computing efficiency, resilience between sea conditions, and early stage design practicality. Notably, the KCS hull shape has been extensively utilized in these investigations because of its thorough geometric documentation and verified experimental data. It is a trustworthy standard for assessing how bow design affects hydrodynamic resistance because of these features. Because of its thorough geometric documentation and verified experimental database, the KCS hull shape is frequently

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Review article

Table 1. Summary of research methods on bulbous bow analysis.

Method	Description	Key elements	Source
Experiment tests in towing tank	Uses physical scale models in specialized facilities to directly measure resistance and observe wave patterns. Considered the most precise approach and the “gold standard” for validating numerical results.	Scale models, towing carriages, dynamometers for force measurement, and laser systems for sinkage and trim measurement	Das et al. (2025); Iqbal et al. (2025); Diaz-Ojeda et al. (2023)
Numerical simulations (CFD)	Employs computational algorithms to solve governing fluid flow equations around virtual hull models. Provides a cost-effective and reliable means to visualize complex flow patterns and rapidly explore wide design spaces.	RANS/URANS equations, turbulence models, Volume of Fluid (VOF) for free-surface capturing, and finite volume discretization	Das et al. (2025); Leal et al. (2018); Ozdemir et al. (2016)
Empirical & Statistical models	Predicts resistance using standardized mathematical formulas derived from regression analysis of historical experimental data. Suitable for rapid evaluation and screening at the preliminary design stage.	Holtrop & Mennen regression method, ITTC-1957 friction line formula, and Kracht design charts based on geometric form coefficients	Ziylan and Nas (2022); Leal et al. (2018); 20. Shen et al. (2025); Tran et al. (2021)

used as a benchmark model in hydrodynamic research and is a typical reference for assessing how bow design affects ship resistance.

The primary objective of this study is to provide a comprehensive review of previous research on the geometric effects of the bulbous bow on the hydrodynamic resistance of KCS-type container ships. The investigation examines the effects of important geometrical components on wave-making resistance, overall resistance, and flow behavior close to the bow. This study offers a methodical review of how geometric changes to the bulbous bow affect the KCS container ship's hydrodynamic resistance. This review highlights the effects of key geometric parameters such as bulb height, width, length on flow behavior, wave-making resistance, and total resistance, and summarizes findings from experimental, computational, and empirical studies. The insights gained emphasize the need of enhancing bulb design to increase energy efficiency and operational performance, as well as future research opportunities in multi-objective optimization, CFD-based parametric analysis, and AI-assisted hull form creation.

2. RESEARCH METHOD

2.1. Classification of research approaches

Three primary methods are usually used to investigate the geometric implications of bulbous bow configurations on benchmark container ships like the KCS: empirical–statistical models, CFD-based numerical simulations, and experimental towing tank testing. In order to directly measure resistance and see wave patterns utilizing towing carriages, dynamometers, and laser-based systems, towing tank studies use physical scale models. These experiments are considered the standard by which other methods are validated [14, 15]. Through the use of turbulence models and VOF methods for free-surface capture, CFD simulations solve the RANS/URANS equations, allowing for comprehensive flow visualization and effective parametric exploration of bulb designs [3,4]. Rapid resistance estimations for initial design screening are provided by empirical methods, which depend on regression-based formulations such as the ITTC-1957 friction line, Kracht charts, and the Holtrop & Mennen technique [18,19]. As shown in Table 1, these complementary techniques work together to offer high-fidelity hydrodynamic analysis as well as quick early-stage assessment.

2.2. Bulbous bow geometry and design parameters

A bulbous bow's geometry is mainly defined by a series of linear parameters that establish its basic measurements in relation to the ship's hull [20]. The most significant variable is the protruding length, which indicates the bulb's forward extension from the front perpendicular and controls the amplitude and phase interaction of the wave system the bulb creates with the waves produced by the hull [21]. The greatest breadth indicates the bulb's widest transverse width at the forward perpendicular; it has a substantial impact on the amplitude of bow wave generation by influencing the displaced volume [20].

The centroid height, which directly regulates the bulb's submergence depth and, consequently, its efficacy under various loading and draft conditions, is the vertical distance between the baseline and the centroid (or foremost reference point) of the bulb cross-section [7]. A ratio based explanation of bulb scale and proportionality

Table 2. Quantitative effects of bulbous bow geometry on hydrodynamic resistance.

Parameters	Variation	Δ Total resistance (%)	Source
Bulb length	+ 14%	+ 0.58	Das et al. 2025
Bulb length	- 5%	- 0.12	
Bulb height	+ 2%	- 1.06	
Bulb breadth	+ 10%	+ 0.55	
Bulb breadth	- 25%	- 0.07	
Combination D33	(+ 0.4% bulb length; - 1.5% bulb width; - 2.2% buld tip height)	- 1.14	Maasch et al. (2018)
Combination D10	(- 0.1% bulb length; +0.2% bulb width; - 6.9% buld tip height)	- 0.82	
Combination D24	(+ 0.2% bulb length; + 0.5% bulb width; - 7.4% buld tip height)	- 0.73	

may be found beyond these fundamental linear dimensions using non-linear and area based characteristics that were first established in Kracht's (1978) classic geometric framework [7]. The cross-sectional area at the forward perpendicular is frequently normalized against the ship's midship section area in order to evaluate relative geometric intensity [7,20]. Its longitudinal wave interaction potential is reflected in the lateral area, which is the projected area of the projecting bulb on the longitudinal center plane. By expressing the protruding bulb volume as a percentage of the vessel's overall displacement volume, the volumetric parameter provides a global measure of geometric magnitude. Bulbous bows are further categorized based on cross-sectional shape in addition to dimensions and ratio-based characteristics [20]. Because it concentrates volume in the lower portion, the Δ-type (delta) bulb is especially well-suited for vessels with U-shaped fore-sections and high draft fluctuation. The rounded contour of the O-type (elliptical or circular) bulb allows for better resistance to slamming and spatial flexibility for equipment placement on a variety of hull shapes. The Nabla bulb is often considered to be very successful in reducing wave amplitude and improving seakeeping performance, particularly for cargo and oil tankers. It concentrates volume in the top area and blends in seamlessly with V-shaped fore-sections.

3. RESULTS AND DISCUSSION

3.1. Influence of geometric parameters on resistance

The geometric arrangement of the KCS's bulbous bow has a significant impact on its hydrodynamic resistance, however the degree and direction of this influence vary depending on the particular parameter modification. Table 2 summarizes the fact that resistance decreases are not necessarily proportionate to improvements in bulb length. A 14% increase in bulb length causes a minor increase in overall resistance (+0.58%), whereas a 5% drop causes a marginal decrease (−0.12%) [14]. These findings suggest that instead of improving wave cancellation, excessive elongation may worsen hydrodynamic performance. In ranges of modest adjustment, bulb height shows a more positive tendency. The overall resistance decreases by around 1.06% with a 2% height increase, indicating better wave interference and pressure distribution close to the bow area. Different bulb widths, on the other hand, exhibit limited sensitivity: a 10% increase in bulb width results in a 0.55% increase in total resistance, but a significant 25% drop only results in a little decrease (−0.07%). In resistance optimization, width is not the primary governing parameter, as seen by this very tiny fluctuation. Compared to single-variable modifications, parametric combinations seem to be more successful. With a minor increase in bulb length (+0.4%) and decreases in breadth (−1.5%) and tip height (−2.2%), the D33 design achieves an overall resistance reduction of 1.14% [5]. This demonstrates that combined multi-parameter refining produces more noticeable gains than discrete geometric adjustments. Overall, the quantitative data shows that rather than drastically altering any one geometric component, the best hydrodynamic performance is obtained by coordinating and moderately adjusting bulb length, height, and width. A total of 868 CFD simulations were carried out across 40 geometric variations of the KCS in a comprehensive parametric investigation to identify effective bulbous bow designs [5]. The study offered a thorough assessment of how integrated geometric improvements impact overall resistance characteristics by methodically altering bulb length, breadth, and tip height in relation to the initial KCS baseline.

3.2. Optimization approaches for bulbous bow design

Building on prior understanding of geometric sensitivity, this section focuses on sophisticated optimization techniques for bulbous bow design [5]. In order to improve wave interference effects, modern research uses parametric and localized optimization techniques like Free-Form Deformation (FFD) and NURBS-based modeling, which allow for precise and adaptable modification of important geometric variables like protruding length, bulb breadth, and tip height. In addition to single-objective refinement, contemporary methods are increasingly using limited optimization frameworks and multi-objective methods that concurrently lower resistance while preserving critical hydrostatic properties including displacement, stability, and Longitudinal Center of Buoyancy (LCB). In order to maintain operating viability and safety, deviations from these criteria are usually limited to ±1% [8]. Surrogate-based global optimization (SBGO) techniques are frequently used to reduce the high computational cost of high-fidelity CFD simulations. Rapid exploration of vast design spaces is made possible by techniques like Kriging, Radial Basis Functions, and Response Surface Methods, which approximate the target function. These techniques significantly cut down on calculation time while maintaining strong optimization capabilities when used with sophisticated search algorithms like NSGA-II or Whale Optimization Algorithm (WOA) [8]. The emphasis has shifted from single design-point optimization to performance evaluation throughout the whole operating envelope, including changes in speed and draft, with the advent of scenario-based and AI-integrated frameworks more recently [2]. Further improving the speed and accuracy of resistance prediction in early-stage design is the use of machine learning models, such as hybrid Case-Based Reasoning (CBR) techniques trained on CFD and experimental datasets [18].

3.3. Design recommendations for optimal bulbous bow geometry

In order to optimize the KCS's bulbous bow geometry, its major linear dimensions, cross-sectional shape, and operating circumstances must all be balancedly refined. Experimental and numerical investigations show that a comparatively slimmer and longer bulb is often better, especially when it comes to lowering wave-making resistance for moderate to high Froude values. Excessively short or blunt bulbs generally increase total resistance, whereas longer, narrower V-shaped forms enhance wave interference and delay wave breaking. Small vertical or angular adjustments such as slightly raising the bulb tip or applying minor rotational alignment can further improve pressure distribution and reduce resistance.

Operational conditions also play a key role. A slight bow-down trim (around 0.25°) at optimal interference depth often yields better performance, with trim having a stronger influence than draft variations. Although bulbous bows are typically more effective at higher Froude numbers, recent designs show measurable gains even at lower speeds through reduced wall shear stress and turbulence.

Surface condition is equally critical, as localized fouling on the bulb can disproportionately increase resistance despite its limited wetted area. Overall, consistent resistance reduction requires longer, slender bulbs combined with appropriate trim conditions [2,5,14].

4. CONCLUSION

This paper shows that the KCS hydrodynamic performance depends on balanced, integrated adjustments of the bulbous bow rather than major changes to a single parameter. Moderate, coordinated modifications in bulb length, height, and width provide more reliable resistance reductions than isolated changes. Robust evaluation still requires combining empirical methods, high-fidelity CFD, and towing tank experiments. Current advancements in AI-assisted frameworks, surrogate-based techniques, and multi-objective optimization further improve design flexibility and efficiency across a range of operating conditions. Priority should be given to multi-condition robustness and data-driven approaches in future optimization efforts to achieve consistent and energy-efficient bulbous bow designs.

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