EXPERIMENTAL ANALYSIS OF BULBOUS BOW OPTIMIZATION FOR RESISTANCE REDUCTION IN SMALL SHIPS

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1. **ABSTRACT:** The bulbous bow is one of the most commonly used hydrodynamic applications for wave-making resistance reduction and fuel saving in ships. However, it is remarkably sensitive to geometrical configuration, wherein poorly designed arrangements can result in an increase in resistance rather than a reduction. Though a substantial amount of work has been accomplished on bulbous bows for bigger ships, smaller ships are surprisingly unrepresented in available literature despite having a higher sensitivity level for geometrical variations. In this research, this issue is examined in a systematic experiment to compare five bulbous bow designs with a baseline ship hull. A special facility with repetitive hydrodynamic forces was used to test unsteady flow phenomena around each bow shape. The hydrodynamic force index was normalised in a way to indicate flow stability, calculated based on unsteady pressure forces in the stagnation part of each bow, with smaller values of this index showing stable flow conditions when closely attached to the bow, while large values characterise flow separation, irregular waves, and high hydrodynamic instability. Results show significant performance variation among the tested designs. The best configuration exhibited very low hydrodynamic force index values of 3 - 4, reflecting good stability of flow, whereas values up to 8 - 9 were reached for less performing designs and the baseline hull, indicating high flow separation. These results confirm the strong dependence that exists between hydrodynamic stability and bulb geometry. This paper presents an experimental basis that underpins bulbous bow optimization in small ships and gives further backing to the development of geometry-driven design guidelines going beyond purely numerical approaches.

2. INTRODUCTION

Hydrodynamic optimization techniques provide immense benefit in increasing efficiency and environmentally friendlier ships. Taking into consideration all other various appendages, which were fitted on ships, it has been found that bulbous bows are among those that are most successful in combatting wave resistance, particularly when Froude numbers are moderate to high. This technique creates a supplementary wave, which destructively superimposes with wave components from the bow [1].

Although this design technology has been applied for a long period, it also has very large gaps. All these design technologies are relatively specific to ships. These models are incapable of showing directions for small ships. Moreover, it has been seen that the type of response of the bulbous bow due to operation conditions, geometrical parameters, and dynamic interaction between ships and flow around bows has been affected. This has been particularly important for small ships, as these ships are relatively sensitive to geometrical parameters [2].

Nonetheless, this challenge would be addressed in this research work since a controlled experiment would be conducted in this research with the objective of evaluating the impact of bulb shapes on hydrodynamic stability through an oscillation test facility. This research, in evaluating alternative designs for a bulb shape to a test vessel, seeks to contribute to design rules being developed in a manner that would be determined experimentally as opposed to being determined in a simulation. This would help in gaining insight into small vessel bulbous bow performances, which would lead to improvement in optimization techniques with enhanced access [3].

3. LITERATURE REVIEW

There has been considerable development in researchers working on and optimizing bulbous bow shapes in the last two decades, from towing tank experimentations to more parametric studies. Some of the pioneering works, including those of Tatsumi *et al.* in 2010 [4], indicated that wave interference effects are effective in resistance reductions, establishing a new optimized bow design for an NBS ship type.

For many years, it has been realized that bulbous bow design represents one of the most significant factors that may help improve hydrodynamic performance and reduce ship resistance. Computational methods have recently been applied to further develop hull designs. In 2001, Peri and Rossetti [5] used CFD-based optimization for hull forms and demonstrated the great potential of numerical methods for improving hydrodynamic efficiency. Later in 2005, Sharma and Sha [6] addressed practical design issues pertinent to small crafts and once again confirmed that the shape of the bulb is of crucial importance for any reduction in resistance.

In recent years, during the 2010s, research has increasingly targeted the integration of experimental and numerical approaches. Zhang and Ma [7] focused on hull form optimization for minimum wave-making resistance, whereas Luo and Guo [8] carried out simulations of viscous flow around bulbous bows to analyze the flow pattern and contribution of components to resistance. Campana *et al.* (2006) [9] discussed shape optimization techniques based on the use of CFD, while pioneering work was set for multi-objective design approaches. Further, in 2014, Filip *et al.* [10] presented bulbous bow retrofitting on containerships using open-source CFD tools; this shows the practical uses related to existing vessels.

Outstanding methodologies emerged in the middle of the 2010s in the form of parametric design and optimization algorithms. Chrismianto and Kim [11] conducted resistance minimization using cubic Bezier curves and curve-plane intersection methods based on CFD. Multi-objective genetic algorithms coupled with surrogate models were adopted by Lu *et al.* [12] in 2019, and Lu and Chang [13], in 2016, in optimizing bulbous bow shapes in a number of operating conditions and revealed speed-dependent optimum bulbous bows that realized speed-dependent resistance reduction over different speeds. Yin *et al.* [14] researched the slow-steaming conditions relevant to container vessels through numerical and experimental approaches. Park *et al.* [15] have considered the effects of changes in the variations of trim along with that of bulb shape variation on container ship resistance and prepared an outline of its interactions in geometry and operational conditions. More recent works have extended the research to special-purpose and inland vessels. Kamal *et al.* [16] investigated resistance component and wave profile variations with bulbous bow for small ships, while Abo El-Ela *et al.* [17] made an extensive review on bulbous bow shapes and their performance impact. In 2024, Bappy and Hasan [18] showed that bulbous bows work well in inland vessels in Bangladesh, where this concept might lead to some fuel-saving and efficiency enhancement.

Very recent research has gone a step further to quantify the hydrodynamic effects of bulb geometry. Liu *et al.* [19] studied the hydrodynamic derivatives determined by different bulb shapes through hybrid drifting and circular motion tests. Le *et al.* [20] examined the added resistance due to bulbous bow shape in regular head waves; this revealed the sensitivity of ship resistance to geometric changes under real sea conditions. All these works together are indicative of a clear trend of evolution from empirical geometric design to state-of-the-art computational and experimental optimization approaches for better hull designs, fit for diverse operational scenarios.

While the literature extensively covers bulbous bow designs for large vessels, such as container ships under slow steaming conditions, notable gaps remain in small ship applications, where geometric sensitivities and flow instabilities significantly impact resistance profiles. This study bridges these gaps via systematic lab experiments on five bulbous bow variants, yielding frequency-dependent thrust values hydrodynamic force values ranging from 3 - 4 (optimal) to 8 - 9 (poor stability) and providing empirical design guidelines absent in prior works.

4. METHODOLOGY

Figure 1 summarizes the phases of this research's methodology.

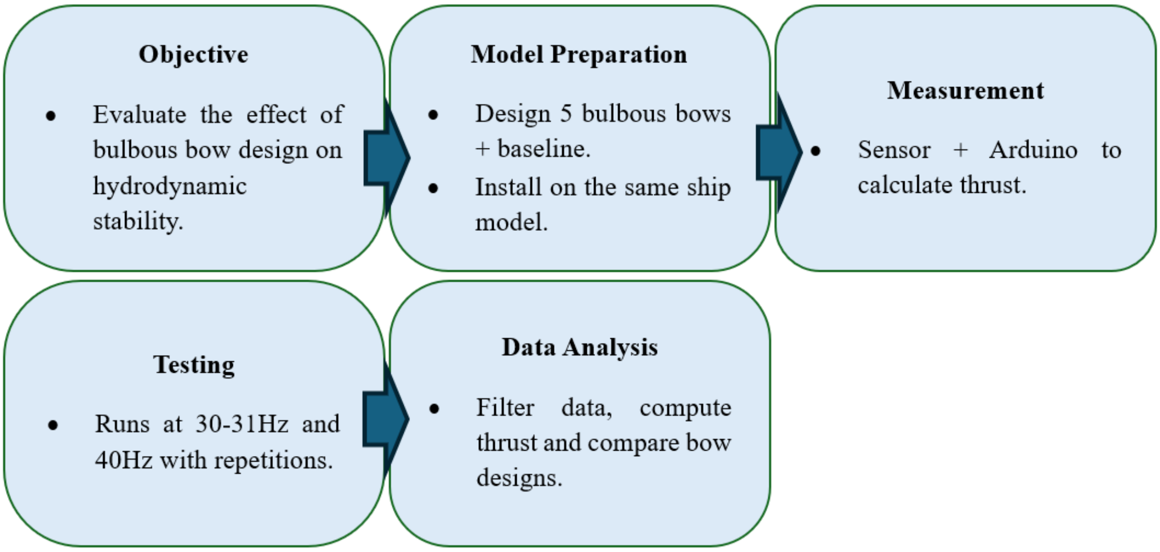

Figure 1: Methodology Layout.

4.1 Experimental Framework

The present experiment employed a controlled and repeatable experimental design that tested the performance of five bulbous bow configurations with a common hull shape. In essence, a major objective of this experiment was to critically investigate how geometrical variations influence flow stability and wave-structure interactions when excited in a harmonic manner. These experiments were conducted in a lab-based setup that employed a customized oscillating test rig that simulated flow excitations with a vessel operating characteristic.

All bulbous bow models were produced using high-precision 3D printing in order to provide exact geometrical characteristics. Bow models were in turn installed on a common small ship forebody, which eliminated differences in hull form parameters. The experiment employed an Arduino data acquisition system providing measurement of the thrust index, which is a dimensionless quantity that describes flow coherence and stability in near-bow area. The thrust has been proved as a flow stability indicator in experiments with small-scale hydrodynamic devices.

Figure 2 shows the experimental setup that consists of the submerged model hull in red combined with the test bulb in blue.

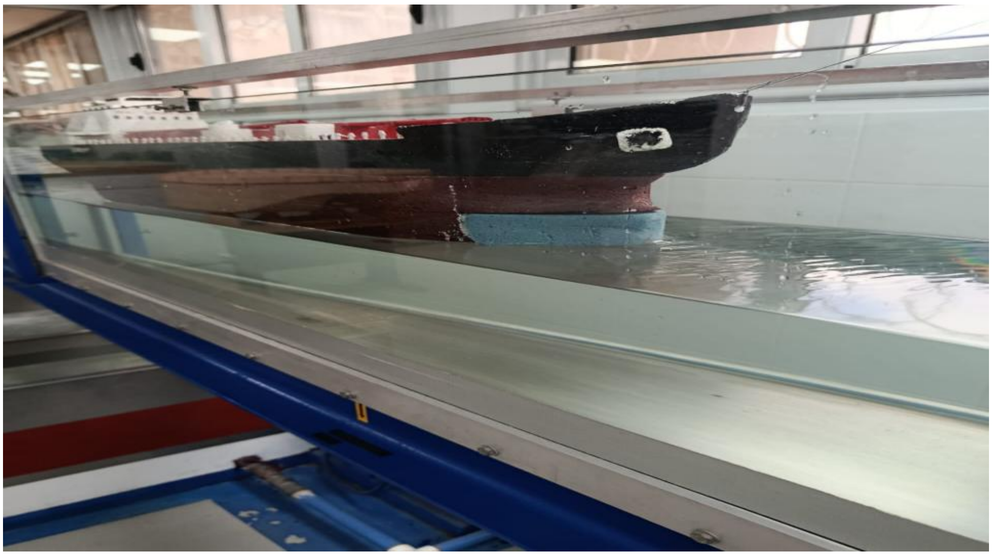

Figure 2. Experimental test setup of the small ship model with an attached 3D-printed bulbous bow in the water tank.

These experiments were all carried out using a set of two oscillation frequencies, namely 30-31 Hz and 40 Hz, which were representative of low and moderate oscillations. A minimum of 15 replicates were taken for all test scenarios to offer a form of statistical representation. The data acquisition system, shown in Figure 3, employed used recorded values of both instant and peak values of readings of thrust, from which average performance values were derived for all the bows.

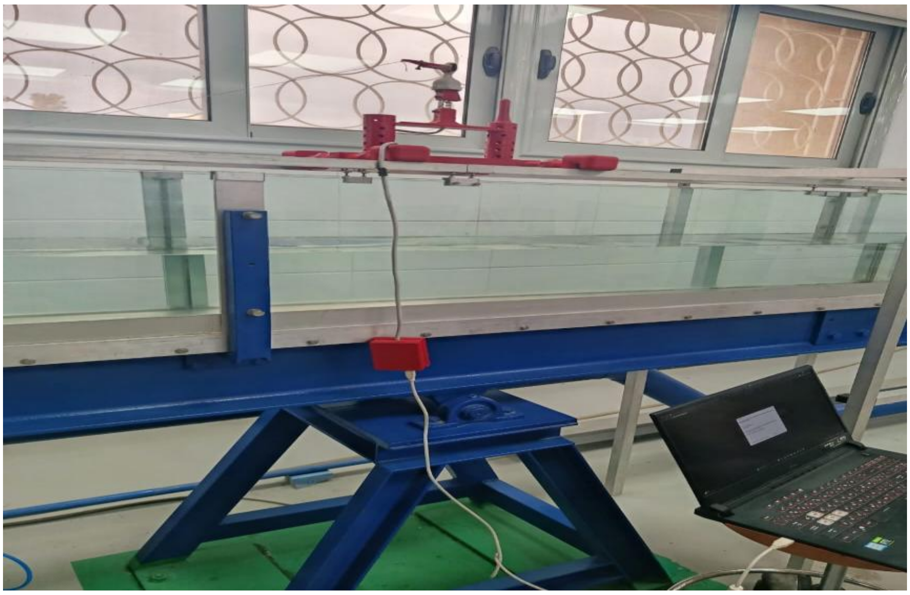

Figure 3. Data acquisition system: pressure sensor connected to an Arduino Uno.

4.2 Measurement System and Data Acquisition

The Arduino Uno microcontroller is used as a key data acquisition system component. A calibrated pressure-vibration sensor was placed along the stagnation point of the bulb to measure dynamic changes of local hydrodynamic properties. The data collected from this sensor was processed in real-time to obtain values for instantaneous thrust, with high frequency noise in pressures removed.

A protocol of measurement was employed that consisted of a system calibration for all frequencies to set a sensor baseline, a10-second stabilization period before data recording, data acquisition for 90 seconds per trial, calculation of maximum and average steady-state values of thrust in real-time, and post processing for elimination of erroneous data beyond 95% confidence limit.

This ensured that for every result reported for the thrust, a constant hydrodynamic condition representative of a particular bow configuration was involved.

4.3 Experimental Procedure

Each arrangement of bulbs in a bow from were numbered Bow 1 to Bow 5, as well as a normal bow, referred to as Bow 0, was considered as shown in Figure 4. The experiment involved the installation of the bow model on the standardized forebody, operating with 30-31 Hz input rate and processing all thrust outputs, repeating the test at 40 Hz., and analyzing the relationship of the thrust performance with respect to the baseline hull.

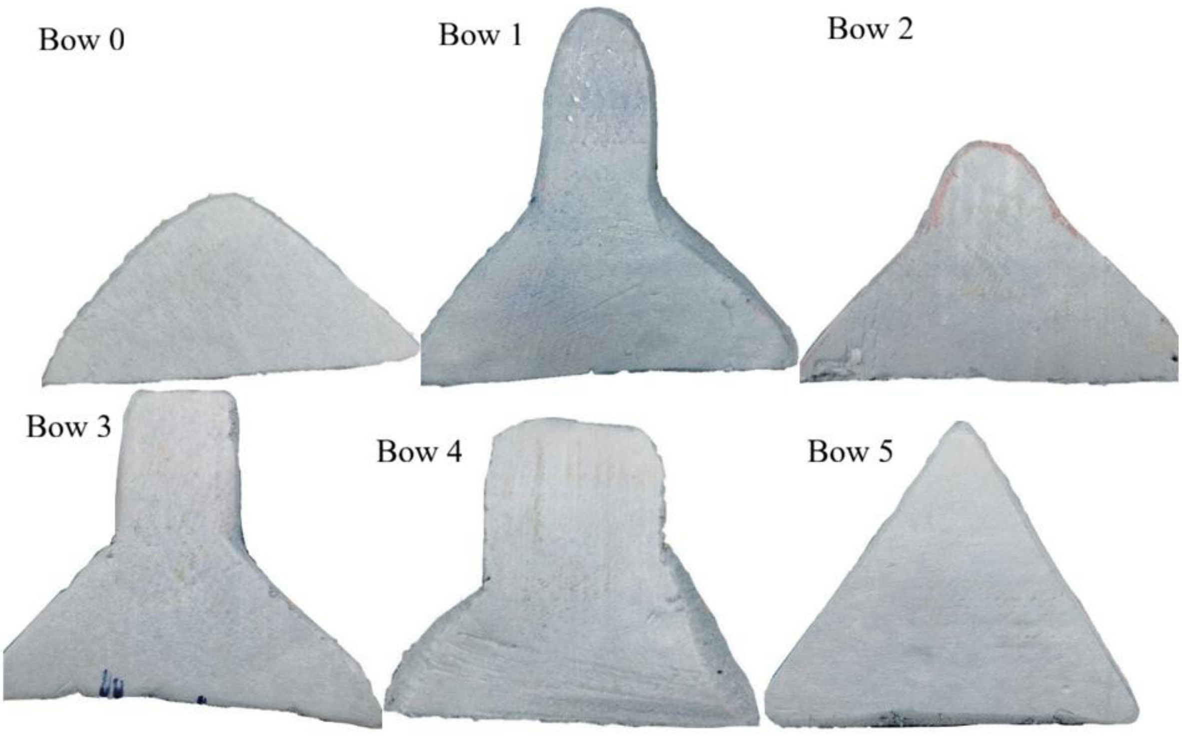

Figure 4: Different Bulbous Bow Designs.

The thrust index was considered a direct measure of hydrodynamic coherence; it meant that high values of thrust correspond to flow separation, wave irregularity, and instabilities in hydrodynamical flows while small values relate to easy, stable, and well-attached flow. This approach translates to a systematic experimental computational model, which has been used in recent works concerning bulbous bow optimization.

4.4 Hydrodynamic Force Index

These results of unsteady pressure variations on the bulb stagnation point were further non-dimensional to obtain the Hydrodynamic Force Index (HFI) parameter, which estimated the levels of unsteady hydrodynamic forces generated due to oscillatory interactions between the bow-shaped body and surrounding fluid flows.

A high value of HFI corresponds to strong variations of pressure forces related to flow separation, wave irregularities, and hydrodynamical instability known to be wave resistance contributors. A low value of HFI reflects typical preferences for smoother pressure force distribution and improved flow attachment and hydrodynamical harmony around the bow.

Though the test rig does not provide a simulation of a conventional towing tank test to determine ship resistance, in this case, a forced vibration with a periodic acceleration of a liquid flow takes place, which ensures a wave flow similar to one generated by ship resistance. Therefore, the application of the hydrodynamic force index to define this test index appears to be reasonable.

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5. RESULTS AND DISCUSSION

The experimental dataset has shown distinct, configuration-dependent patterns of hydrodynamic stability. Figure 3 below lists values of hydrodynamic force index for all bow configurations for both test frequencies. The baseline hull, with Bow 0, showed highest values of thrust, which reached 8 and 9 for frequencies of 30-31 Hz and 40 Hz, respectively. These values are indicative of serious flow separation and a harmful wake.

On the other hand, Bow 1 showed the minimum performance in all tests, with hydrodynamic force index values restricted to 3-4. This reflects a stable flow condition with little turbulence and regular wave patterns. While Bow 2 and Bow 3 showed reasonable performance improvement, with hydrodynamic force index values between 5-7, their moderate stability illustrates a tendency towards a regain of attached flow but without restoring original performance. Furthermore, Bows 4 and 5 showed the most agreement with the baseline hull, which reached a value of 8 for hydrodynamic force index at 40 Hz.

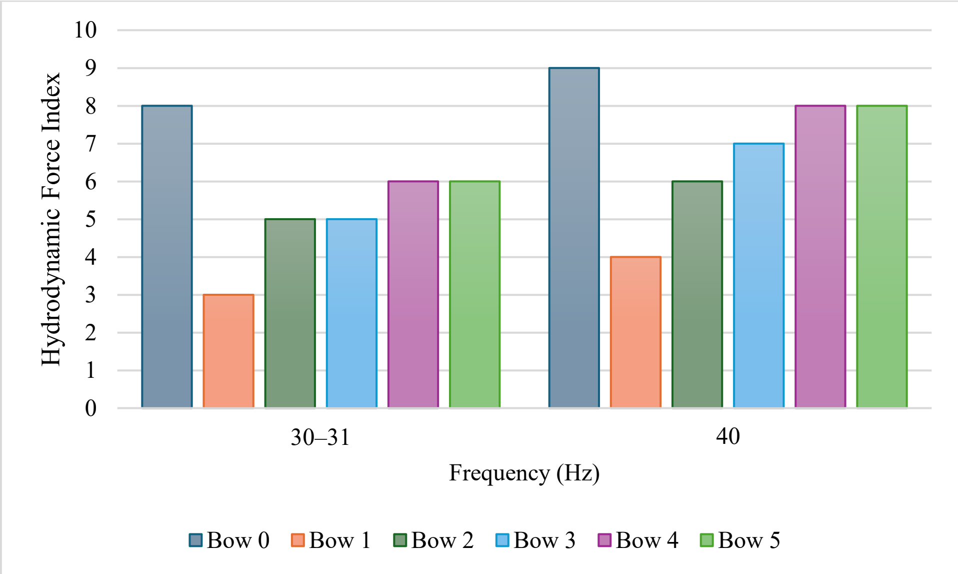

Figure 5: Thrust value for bulbous bow shapes in different current frequencies.

These tests prove that a refined shape with a proper scaling of length to breadth can lead to a marked improvement in flow stability without needing major design changes.

In all cases, however, performance increased with the higher frequency of 40 Hz, which suggests that the response of the hull to hydrodynamic forces takes a frequency-dependent form and that certain bulbous bow designs work better with oscillating flow conditions.

Comparison of relative hydrodynamic performance of test designs of the bow hulls gives a distinct group for stability. The test design has a profoundly stable performance and was used as a standard for all other designs. On the other hand, for a design with a relatively low performance, the stability has been found to be low with a marked flow separation, a slightly better design has instabilities despite a certain improvement, whereas for other designs, values of moderate stabilities are obtained. These designs also showed certain improved flow attachment characteristics for higher frequencies. Other designs were found near to a moderate to good stability range, which was close to that of high stability regions. The better modified designs of the bow hulls showed a good to very good stability performance, which was close to that of standard designs, with an optimal hydrodynamic performance.

6. CONCLUSIONS

One of the most prominent applications of hydrodynamic optimization regards efficiency and environmental vistas of modern ships. Among a huge number of bow modifications developed in the past century, it has been determined that bulbous bows are most efficient wave resistance-reducing devices for ships when moderate to high Froude number operation conditions are taken into consideration. This device works as a secondary wave generator, which interferes destructively with waves produced by bow, hence reducing the dominant portion of total resistance offered to ships when moving around their speed.

Although it has been in use for a long time, it has to be accepted that even now, there are still significant gaps in bulbous bow design. This has been particularly true for designs that were very vessel-specific, especially those that lack proper models but are able to offer small vessel designs. Also, it has been mentioned that among other factors, bulbous bow hydrodynamics are especially impacted by vessel operating conditions, geometry ratios, as well as bow motion and flow interaction. This becomes particularly important in small ships where small geometry changes would result in substantial effects.

This research fills this research gap by performing a controlled experiment to examine, using an oscillation test facility, how bulb shape affects hydrodynamic stability. A comparative test of different bulb designs against a control vessel design will help guide design methodology, rather than relying purely on simulation. This research showed that Bow 1 exhibited the least resistance among all the proposed bulbous bow designs. The findings work to enhance knowledge of small vessel bulbous bow performance and will help facilitate simulation-based optimization in this area of industry.

7. DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES

During the preparation of this work, the author(s) used DeepSeek, Copilot, and Google Gemini in order to summarize existing research, and refine language. After using this tool/service, the author(s) reviewed and edited the content as necessary and take(s) full responsibility for the content of the publication.

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