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Hull Form Design Analysis With Variations Of Block Coefficient (Cb) And Cross-Sectional Area (CSA)

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ABSTRACT –This study investigates the influence of hull-form variations on the hydrodynamic performance of a two-passenger leisure boat designed for reservoir operation. Five hull models were developed with deadrise angles of 13°, 15°, 17°, 19°, and 21° to examine how changes in the block coefficient (Cb) and cross-sectional area (CSA) affect total resistance and maneuvering characteristics. Numerical calculations and Computational Fluid Dynamics (CFD) simulations were performed for validation. The 13° deadrise model, which had the highest Cb, exhibited the lowest total resistance of 0.92 kN, while MATLAB-based maneuvering analysis showed the largest turning radius of 9.32 m. Conversely, the 21° deadrise model achieved the smallest turning radius of 5.91 m. At a Froude number (Fn) of 1.37, the boat operates in the planing regime, where a fuller hull enhances hydrodynamic lift and reduces wetted surface area, resulting in lower drag but reduced maneuverability. Thus, the Model C hull with a 13° deadrise angle and the highest *Cb* value becomes the most suitable option for operation in the reservoir used as the study's case location. Although this model exhibits the largest turning radius, at 11.98 m, the value remains within the minimum maneuvering width available in the reservoir (approximately 22 m) thereby still meeting the operational criteria. The results offer practical insights for designing efficient leisure boats optimized for calm-water environments such as reservoirs.

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INTRODUCTION

Tourist boats operating in reservoirs and lakes are generally based on conventional designs that have not yet adopted modern hydrodynamic principles. As a result, several operational issues are often encountered, including high fuel consumption due to excessive hull resistance, limited speed and stability, and poor maneuverability caused by a large turning radius [1].

Previous studies have emphasized that the deadrise angle is one of the most influential geometric parameters governing a vessel's hydrodynamic performance, as it directly affects resistance, lift generation, and directional stability [2]. Other investigations have shown that optimizing the Curve of Sectional Area (CSA) can reduce wave-making resistance and improve maneuvering efficiency [3], while the block coefficient (Cb) significantly influences overall fuel efficiency and hydrodynamic behavior [4]. Furthermore, geometry-based optimization approaches have been successfully applied to the design of small fishing vessels, where principal dimensions and hydrostatic curves are determined according to key hull ratios [5].

Building on these insights, the present study focuses on analyzing the influence of deadrise angle variations (13°, 15°, 17°, 19°, and 21°) on changes in Cb and CSA, and how these parameters affect total resistance and maneuvering capability of a two-passenger leisure boat operating in calm-water environments such as reservoirs. The resistance was evaluated using both numerical calculations and Computational Fluid Dynamics (CFD) simulations, while the maneuvering performance was assessed through MATLAB-based turning calculations using the proposed formula. The findings are expected to provide a scientific basis for developing efficient leisure boat designs with optimized planing performance and improved handling characteristics.

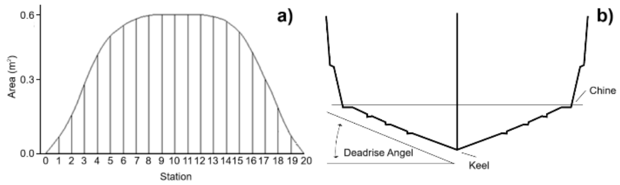


Figure 1. (a) Deadrise Angle, (b) Cross-Sectional Area (CSA).

To strengthen the scientific contribution, it is worth noting that previous studies commonly employ the Nomoto equation to predict turning radius, while the influence of the block coefficient (Cb) is not explicitly incorporated in the formulation. In this study, the authors explore the possibility that variations in Cb may also play a role in maneuvering behavior, particularly for small vessels where geometric differences among hull forms are more pronounced. Based on this consideration, a modified maneuvering formulation derived from the Nomoto approach is developed by introducing Cb as an additional parameter, and its implementation is carried out through MATLAB-based modeling to obtain turning radius estimates that may better represent the vessel's geometric characteristics. This approach is intended to encourage further discussion and stimulate subsequent research on the involvement of geometric parameters in maneuvering models for leisure craft operating in calm inland waters.

METHODS

Resistance

A clear understanding of ship resistance is fundamental to assessing hull performance and producing accurate resistance predictions. Ship resistance refers to the hydrodynamic force that opposes a vessel's forward motion as it travels through water, primarily resulting from the interaction between the hull surface and the surrounding fluid flow [6]. The main component of this force is the viscous resistance, which consists of both frictional resistance caused by shear stresses between the water and the hull surface and form resistance, which arises from the hull's geometric configuration (Savitsky, 1964) [7]. The total resistance acting on a vessel RT, can be expressed as:

$$R_T = C_T \times \frac{1}{2} \times \rho \times v_s{}^2 \times S \quad (1)$$

Where C_T is the total coefficient of resistance, ρ is sea water density (*kg/m³*), V_s is the ship's service speed (*m/s*), and S is wetted surface area (*m²*) [7].

The relationship between resistance and vessel speed is commonly described using the Froude number (F_n), which characterizes the dynamic similarity between gravitational and inertial forces acting on the hull [8]. The Froude number is defined as:

$$F_n = \frac{V_S}{\sqrt{gL}} \quad (2)$$

Where g is the gravitational acceleration (*m/s²*) and L is the length at the waterline (*m*).

This non-dimensional parameter plays a crucial role in identifying the hydrodynamic regime of operation whether the vessel behaves as a displacement or planning craft. At higher F_n values, hydrodynamic lift becomes dominant, reducing the wetted surface area and altering the balance between frictional and wave-making resistance [9].

Manuverability

Maneuverability refers to a vessel's ability to turn or change direction while underway. This capability plays a crucial role in ensuring both the safety and operational efficiency of a ship [10]. The main factors influencing maneuverability include the hull form, propulsion system, steering mechanism, and the loading condition of the vessel.

In addition, several other parameters also affect a ship's maneuvering performance, such as vessel speed, trim, draft variation, longitudinal position of the center of buoyancy, length-to-beam ratio (L/B), propeller diameter, rudder area, and keel dimensions [11].

Recent studies on leisure and passenger vessels have demonstrated that variations in hull design, including the adoption of catamaran and stepped-hull configurations, significantly influence a vessel's comfort, stability, and maneuvering efficiency [12][13][14].

In this study, a simplified predictive expression for the turning radius is introduced as a preliminary attempt to capture the influence of ship form coefficients on manoeuvring performance. The formula is heuristically derived from the basic structure of Nomoto-type manoeuvring models [15], but it is not intended as a replacement for such established approaches. The proposed relationship is given by:

$$R = \frac{L_{pp} \times V^2 \times \sqrt{L_{pp}}}{k \times g \times C_b \times \cos(\theta_{\text{rad}})} \tag{3}$$

The constant 12.6 is introduced empirically as a scaling factor to balance dimensional consistency and provide a reasonable order of magnitude compared with conventional manoeuvring criteria.

The aim of this formulation is not to present a validated prediction tool, but rather to explore, in a transparent and simplified manner, how the block coefficient and rudder angle may affect the resulting turning circle. At this stage, the equation remains an approximation; no experimental or numerical validation has yet been conducted.

Meanwhile, the required rudder area, according to BKI (2006), Volume II, Section 14.A.3, is defined by the following equation [16]:

$$A = 1 \cdot 0.9 \cdot 1 \cdot 1 \cdot \left(\frac{1.75 \cdot L_{PP} \cdot T}{100}\right) \tag{4}$$

Rule-based designs following BKI standards have also been widely applied to traditional vessels. For instance, the preliminary design of a 2 GT traditional fishing boat incorporating an additional floating compartment has been developed to enhance safety aspects [17].

The initial stage of this research involved collecting twenty sets of principal dimensions of existing scooter boats, obtained from both reference literature and real vessel data. These data were then processed using a linear regression method to generate a new set of representative principal dimensions [18]. The regression results were used to establish the main design parameters of the proposed leisure boat, as presented in Table 1.

Table 1. Principal Dimensions of the Boat

	Principal Dimension and Parameter Design		
No	Note	Value	Unit
1	LOA (Length Overall)	3,40	m
2	LPP (Length Between Perpendiculars)	2,85	m
3	LWL (Length at Waterline)	2,96	m
4	B (Breadth)	1,50	m
5	H (Height)	0,57	m
6	T (Draft)	0,33	m
7	V (Vessel Speed)	15	knot
8	Cb (Block Coefficient)	0,447	-
9	Cm (Midship Coefficient)	0,579	-
10	Disp. (Displacement)	0,5795	ton

The hull form modeling was conducted using Maxsurf Modeler software to generate a three-dimensional representation of the vessel. The baseline hull design was then systematically modified by adjusting the deadrise angle to 13°, 15°, 17°, 19°, and 21°, as shown in Figure 2. Each deadrise configuration produced distinct variations in the Curve of Sectional Area (CSA), resulting in differences in hull volume distribution and underwater form characteristics.

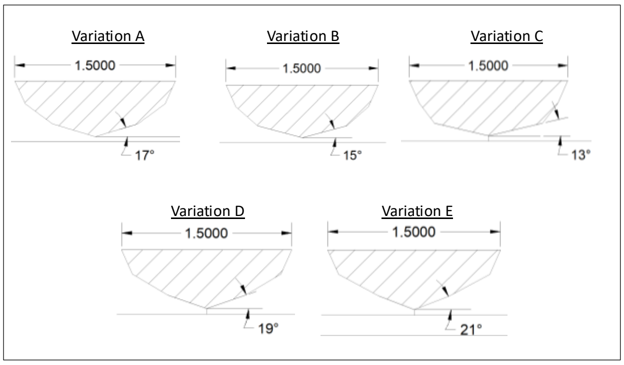
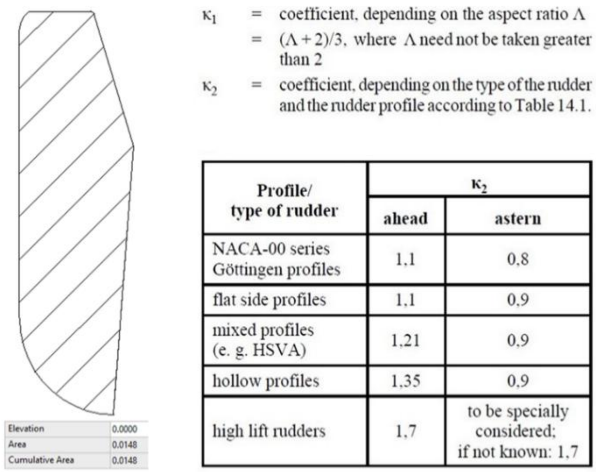


Figure 2. Variations of Deadrise Angle

The next stage involved the rudder design process, in which the designed rudder was applied uniformly across all hull variations. According to BKI (2006), Volume II, Section 14.A.3, the rudder blade area must not be less than the minimum value specified by the following formula:

$$\begin{aligned} A &= 1 \times 0.9 \times 1 \times 1 \times \left(1.75 \times L_{pp} \times {}^{T}/_{100}\right) \\ &= 1 \times 0.9 \times 1 \times 1 \times \left(1.75 \times 2.85 \times {}^{0.33}/_{100}\right) \\ &= 0.0148 \text{ m}^2 \end{aligned} \quad (5)$$

The selected rudder type was NACA-009, with the corresponding rudder coefficient curve and rudder design geometry shown in Figure 3.



Profile/ type of rudder	κ_2 ahead	κ_2 astern
NACA-00 series Göttingen profiles	1,1	0,8
flat side profiles	1,1	0,9
mixed profiles (e. g. HSVA)	1,21	0,9
hollow profiles	1,35	0,9
high lift rudders	1,7	to be specially considered; if not known: 1,7

(a) (b)

Figure 3. (a) Rudder Design, (b) Rudder Coefficient.

At this stage, the principal dimensions of the research object (including overall length, beam, and draft) were defined as fixed parameters to ensure consistency across the hull-form variations derived from linear regression of 20 existing data points. In addition, the operating speed and calm-water conditions were established as constant parameters throughout the entire series of tests.

Subsequently, an analysis of the total resistance was carried out, followed by an evaluation of the maneuverability parameters. The primary parameter examined was the turning radius, which was calculated based on the Curve of Sectional Area (CSA) results using MATLAB software. To assess the influence of the rudder angle on turning performance, simulations were conducted with rudder deflection angles of 35°, 40°, and

45°. These variations allowed observation of the turning circle radius at different steering conditions. The rudder angle values were adjusted by modifying the input parameter θ (theta) within the MATLAB program.

The MATLAB approach employed in this study represents a further development of an existing model, while the resistance calculations were carried out through CFD simulations using Fine Marine version 9.1 and the Bentley Maxsurf Resistance software.

RESULTS AND DISCUSSION

The total resistance values obtained from numerical calculations and CFD simulations are summarized in Table 2. Both methods were conducted under identical operating conditions at a service speed of 15 knots (7.72 m/s). The CFD validation procedure follows the methodology described in Impact of Stepped Hull Design on Speed Boat Performance: A CFD Study [19].
Table 2. Comparison of Ship Resistance Values from Numerical Calculation and CFD Simulations.

Table 2. Comparison of Ship Resistance Values from Numerical Calculation and CFD Simulations.

Variation	Speed	Unit	Resistance (kN)		Error
	Knot	*m/s*	Numerical	CFD	(%)
A (17°)	15	7,72	0,90	0,92	2,0
B (15°)	15	7,72	0,93	0,95	2,1
C (13°)	15	7,72	0,88	0,90	2,2
D (19°)	15	7,72	0,96	0,98	2,1
E (21°)	15	7,72	1,18	1,20	1,7

The results indicate that the CFD-predicted resistance values are in close agreement with the numerical estimations, with deviations within ±2 % for all cases. Such consistency confirms the reliability of both the numerical model and the CFD setup, particularly regarding mesh density, turbulence modeling, and boundary condition definitions. Similar levels of agreement were also reported by previous studies, including “CFD-Based Comparative Study of Axe Bow and Bulbous Bow Designs for Corvette Warship Deployment in Natuna Waters,” which demonstrated that CFD-based resistance predictions can accurately replicate experimental or empirical results when model configurations are properly validated [20]. This consistency reinforces the robustness of the CFD approach used in the present research.

Among the tested configurations, the 13° deadrise hull (Variation C) recorded the lowest total resistance of 0.90 kN, while the 21° deadrise model (Variation E) exhibited the highest resistance of 1.20 *kN*. Although a higher *Cb* normally increases resistance in displacement vessels, in planing conditions (*Fn* > 1.0) a fuller, flatter hull promotes dynamic lift and reduces the wetted area, resulting in lower total resistance (Savitsky, 1964) [7].

This trend indicates that resistance reduction is influenced by a balance between wetted surface area and hydrodynamic lift [19]. Excessively flat hulls (low deadrise) generate higher viscous resistance, whereas overly sharp hulls (high deadrise) experience increased pressure drag due to reduced lift generation.

Overall, moderate-deadrise configurations (15°–17°) provided the most balanced hydrodynamic performance, combining low resistance with stable planing characteristics at a Froude number (*Fn*) of 1.37. The close correspondence between CFD and numerical predictions validates the adopted modeling approach and confirms that the simulation results accurately represent the hydrodynamic behavior of the designed leisure boat.

The next approach focuses on analyzing the vessel’s turning radius at a speed of 10 *knots* to ensure that the boat’s draft is fully submerged. The calculation results of the turning radius, obtained using MATLAB (Figure 6), show variations in the turning radius values for each hull model. These differences occur because the deadrise angle variations influence the block coefficient (*Cb*) of each configuration. The *Cb* value is directly proportional to the cross-sectional area (*CSA*); therefore, every change in the deadrise angle results in a different *CSA* value, which ultimately affects the turning radius outcome. The complete results of the calculations are presented in Table 3 below.

Table 3. Results of Turning Circle Radius Analysis

Turning Circle Angle 35º			
Variation	*Cb*	*Cm*	Radius Turning Circle
E (21°)	0,412	0,511	7,59
D (19°)	0,435	0,537	10,41
A (17°)	0,447	0,579	11,04
B (15°)	0,474	0,592	11,35

C (13°)	0,650	0,512	11,98
Turning Circle Angle 40º			
Variation	*Cb*	*Cm*	Radius Turning Circle
E (21°)	0,412	0,511	6,65
D (19°)	0,435	0,537	9,11
A (17°)	0,447	0,579	9,66
B (15°)	0,474	0,592	9,93
C (13°)	0,650	0,512	10,48
Turning Circle Angle 45º			
Variation	*Cb*	*Cm*	Radius Turning Circle
E (21°)	0,412	0,511	5,91
D (19°)	0,435	0,537	8,1
A (17°)	0,447	0,579	8,59
B (15°)	0,474	0,592	8,83
C (13°)	0,650	0,512	9,32

The results summarized in Table 3 show that the turning radius increases as the deadrise angle decreases. This trend occurs because a smaller deadrise angle produces a fuller hull form, resulting in higher block coefficient (Cb) and midship coefficient (Cm). These parameters increase the hull's lateral resistance and hydrodynamic inertia, thereby reducing its turning responsiveness and producing a larger turning circle. At a rudder angle of 45°, the 13° deadrise hull (Variation C) exhibited the largest turning radius of 9.32 m, while the 21° deadrise hull (Variation E) achieved the smallest radius of 5.91 m. Similar tendencies were observed for smaller steering angles (35° and 40°), confirming that hulls with lower Cb values are generally more responsive to rudder action.

To further evaluate the accuracy of the results presented in Table 3, a comparative analysis was performed between the proposed turning-circle equation and the Nomoto manoeuvring model. This comparison aimed to determine whether the turning-radius values predicted by the proposed method were consistent with those obtained from the established Nomoto formulation. In this analysis, two representative hull variations were selected Variation C (13°) and Variation E (21°) to represent the extreme cases of high and low block coefficients. The comparison, illustrated in Figure 4, was conducted across vessel speeds ranging from 0 to 15 knots to assess the influence of speed and hull form on turning performance.

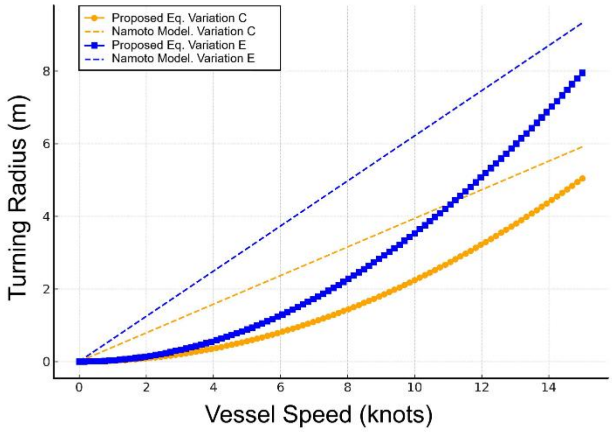


Figure 4. Turning-Radius Comparison of the Proposed Model and Nomoto Model for Variations C and E.

The comparison indicates that our proposed turning-radius equation, although physically motivated, does not yet agree sufficiently with the benchmark Nomoto-based predictions across 0 to 15 knots. The discrepancies are systematic and speed-dependent, showing that a single empirical constant (k) is not universal for this craft and operating range. Therefore, the proposed model should be regarded as preliminary and requires validation before practical use.

CONCLUSION

This study examined the influence of hull-form variations, represented by deadrise angle, block coefficient (Cb), and cross-sectional area (CSA), on the resistance and maneuverability of a two-passenger leisure boat operating in reservoir conditions, with the aim of identifying a hull-form configuration that offers an optimal balance between resistance efficiency and maneuvering agility.

The comparison between numerical calculations and CFD simulations showed close agreement, with deviations within ±2%, confirming the reliability of both approaches. The results indicated that the 13° deadrise configuration (Variation C), which had the highest Cb, produced the lowest total resistance (0.92 kN) but exhibited the largest turning radius (9.32 m at a rudder angle of 45°). Conversely, the 21° deadrise configuration (Variation E) recorded the smallest turning radius (5.91 m at 45°). Although a higher Cb typically increases resistance for displacement hulls, the present study was conducted in the planing regime (Fn ≈ 1.37), where a fuller hull can generate greater hydrodynamic lift and reduce wetted surface, resulting in lower overall drag.

However, when compared to the Nomoto manoeuvring model, the proposed turning-radius equation still exhibited noticeable deviation. This indicates that while the proposed method captures the qualitative influence of *Cb* and speed on turning performance, it requires further validation to achieve quantitative accuracy.

Overall, the findings confirm that *Cb* and deadrise angle play a crucial role in governing both resistance and turning performance of small planing craft. The proposed approach shows promising potential as a simplified predictive model but must validated with experimental and numerical validation before being applied in design practice, , and the results of this study may assist designers in selecting hull geometries that are better suited for recreational vessels operating in calm waters and constrained maneuvering spaces such as reservoirs.

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