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Enhancing Ship Stability: A Comparative Analysis of Single and Double Chine Hull Configurations of Semi-Planning Hull at High Speed

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Abstract

Ship stability could be considered one of the defining aspects of marine transport, as it directly influences the safety and performance of the ship. Past works have found hull geometry critical in the stability issue; however, the impact of various Chinese configurations under different operation scenarios is missing. This paper seeks to address this gap by studying the effects of Chinese single and double geometries on stability, primarily concerning trimming by stern angles in compliance with the High-Speed Craft (HSC) 2000. Annex 8: Monohull Intact Stability Criteria. Stability calculations using Maxsurf software were done concerning angles of the steady heel, the area under the righting levers (GZ) curve, maximum GZ, and initial transverse metacentric height (GMt). The study showed that both Chinese configurations conformed to the prescribed stability standards. Still, the double Chinese configuration showed better results in terms of stability at a 2-degree heel angle, with a GZ value of 1.692 and the highest GMt value in a steady state. Therefore, the research establishes enhanced stability benefits that the users stand to benefit from by adopting double chine configurations relative to single chine styles.

1 Introduction

The same is conventional, as a ship's stability is the essential foundation for naval architecture and has much to do with marine vessels safety and effective functioning. Stability measures how quickly a boat rights itself after being knocked out of alignment by waves and wind. The hull design of a ship has such features as 'chine,' which means there is an abrupt change in the angle of the hull. One study indicated that hull design optimization is vital to enhancing a ship's hydrodynamic behavior and uniform performance [1-3]. Last year, single-chine (one-chine) and double-chive configurations increased in popularity mainly because of their stability in form. Single chine hulls, designed with one hard chine, tend to be more straightforward in construction and efficiency for a specific speed range [4-6]. However, double chine hull form has good stability, such as buoyancy and roll motion damping to the two sharp chines, especially for semi-planning conditions or high-speed craft [7-9]. The performance of these setups has been thoroughly investigated through numerical simulations and hydrodynamic analysis in various operating situations [10-13]. Many studies focused on modeling the ship hull shape and behavior while subjected to different loading conditions.

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For example, Maxsurf's advanced tools allowed an accurate simulation of form stability regarding different environmental boundaries [14-16]. Based on these simulations, the specifics of compliant designs for use in maritime operations, such as complying with international standards like HSC 2000 Annex 8 Monohull Intact to improve safety and serviceability, have been identified [17-19]. Reasons explaining the improved roll damping, healing authority, and eventual righting moments afforded by a double chine hull have been thoroughly addressed in several studies [20-22]. Although some critics suggest that single chine hulls are generally less stable, they also note benefits in terms of speed and maneuverability, which stem from the fact that this construction option is much simpler to build [23-25]. The contradictory findings indicate a requirement for further research to determine the optimal hull design for each type of vessel. The unique aspect of this work is the detailed and systematic comparison between single and double chine hull configurations, using most contemporary numerical tools, including optimization techniques. Therefore, this study introduces new evaluation criteria into the hull form and studies a much more comprehensive set of conditions to provide novel insights; this is important in actively addressing bias from either side towards their preferred optimal shape. This approach's perspective is predicted to be essential for formulating measures aimed at aiding modern naval architecture practices and filling central voids in existing literature, thereby befitting significant progress over safer, more economical maritime vessel design.

2 Literature Review

2.1 Previous studies

Examining the literature on ship hull form optimization reveals that despite tremendous progress in comprehending the hydrodynamic performance and stability of single and double chine hulls, a comprehensive evaluation of these configurations under a range of operational conditions is still lacking. Prior research, conducted by Kim and Lee, has examined chiefly particular factors, such as roll stability and resistance [2]. However, they frequently did not have a comprehensive methodology that takes into account the incorporation of these discoveries into actual hull design optimization, especially in various maritime situations. Furthermore, the utilization of technologies such as Maxsurf in previous studies has been restricted to its extent, frequently failing to thoroughly investigate the intricate impacts of Chinese designs on the overall performance of the vessel. This study seeks to overcome these limitations by utilizing sophisticated stability metrics, such as comprehensive GZ curve analysis and trim assessments, better to comprehend the performance of single and double chine hulls. By aligning these studies with international standards such as HSC 2000, the research provides practical insights that may be used to inform future hull design, ultimately leading to the development of safer and more efficient maritime vessels.

It is the updated form of previous research where single and double chine configurations on a semi-planning hull were not done at high velocities, and trim angles of 1, 2, and 3 degrees were not considered. The present work also offers a more comprehensive analysis as the hull's performance is assessed at different trim angles, which, as already mentioned, were not investigated in most previous studies that concentrated on single or double chine designs. It is important to note that these aspects added to the survey enhance awareness in determining the modifications in trim angle that affect a vessel's performance by examining the stability, energy economy, and resistance. The present investigation presents a broad view in contrast to prior research where attention to one or two factors was primarily given. It significantly improves the understanding of hull shape optimization for the family of semi-planning vessels that work at high speeds (see summary in Table 1).

Table 1. Summary of previous studies on hull optimization

Author	Optimization Subject	Description	Conclusion
Liu and Zhou, 2017 (see in [4])	Application of Maxsurf in hull design	Utilized Maxsurf for hull optimization and stability analysis.	Demonstrated the potential of Maxsurf in optimizing hull designs for stability.

Table 1. *Cont.*

Author and Year	Optimization Subject	Description	Conclusion
Suh and Yang 2018 (see in [3])	Stability assessment of high-speed crafts	Assessed stability of chine hulls using various criteria.	Double chine hulls provided better overall stability for high-speed crafts.
Baso et al. 2020 (see in [26])	Performance Characteristics of a semi planning Ship Hull at High Speed	This study has examined the performance attributes of a semi-planning ship hull when operating at high velocities. The semi-planning hull was designed with three different trim conditions, ranging from bow to stern.	The semi-planning hull's trim in the stern lengthens the air chamber and reduces resistance. The power demand of the semi-planning hull decreases as the stern trim switches to a greater FnV. Conversely, the stability range of a semi-planning hull is reduced when the trim at the stern is increased.
Hu and Cui 2020 (see in [1])	Hydrodynamic performance of hulls	We analyzed single and multi-chine hulls using Maxsurf for performance optimization.	Found that multi-chine hulls offer better stability at the cost of increased resistance.
Kim and Lee 2021 (see in [2])	Comparative analysis of hull forms	Single and double chine hulls were compared, focusing on stability and maneuverability.	Double chine hulls offer superior stability, but single chine hulls have better speed.

2.2 Fundamental of ship stability

In ship stability analysis, the Center of Gravity (CG) and metacentric height (GM) are key factors. The GM is crucial for assessing the vessel's initial stability and how quickly it returns to an upright position after heeling. The righting levers (GZ) is vital for evaluating the vessel's resistance to capsizing. Assuming that the positive direction of y represents starboard, the positive direction of z represents upward, and the ship tilts towards starboard. Refer to the following Equations 1 and 2 for precise mathematical adjustments of these parameters under specific conditions:

$$GZ^{*} = GZ - \left(CG_{y}^{*} - CG_{y}\right) \tag{1}$$

Where:

GZ^{*} = Righting levers-modified

GZ = Righting levers

CG_{y}^{*} = Center of gravity-modified

CG_{y} = Center of gravity

$$GM^{*} = GM - (CG_{z}^{*} - CG_{z}) \tag{2}$$

Where:

GM^{*} = Metacentric height-modified

GM = Metacentric height

CG_{z}^{*} = Center of Gravity-modified

CG_{z} = Center of Gravity

Figure 1 depicts the alteration in the righting levers (GZ) caused by the influence of Water on the Deck (WoD). The righting levers (GZ), is a critical determinant of a vessel's capacity to withstand heeling, which refers to the lateral inclination of the ship caused by external forces like wind or waves. When water collects on the deck, the Center of Gravity (CG) moves upward towards CG-WoD, located at a lower height relative to the deck. This reduces the GZ, as indicated GZ* in the figure, compared to the initial GZ without water on deck. A decrease in GZ reduces the stiffness of the ship's righting moment. Hence, the ship's stability decreases, and the boat will likely capsize. This is even more so when used in conjunction with healing, in which the lateral force not only tilts the ship but reduces GZ at the same time. The illustration clearly shows the intimate connection between WoD and healing, thus emphasizing the need for proper drainage of the deck and the design of the hull in order not to worsen its effects on stability.

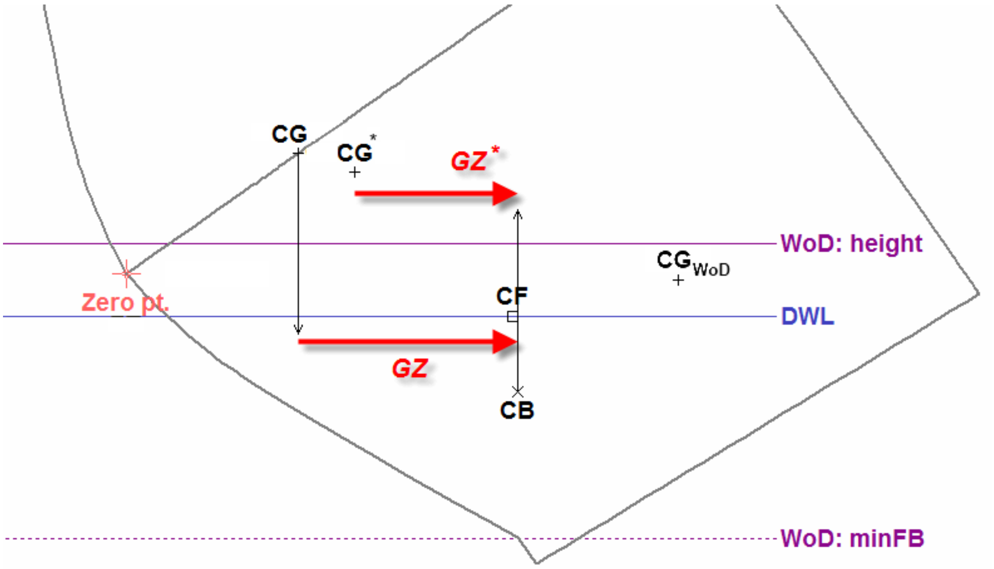


Figure 1. Change in GZ due to water on deck [27]

2.3 International maritime organization high-speed craft 2000

The International Maritime Organization High-Speed Craft 2000 (IMO HSC 2000) assumes a vital role in a high-speed craft's safety, strength, and performance standards by introducing strict criteria concerning structural integrity, stability, and operational safety [29]. However, unlike a regular ship that generally travels at relatively low speeds, this type of regulation is necessary for vessels running at much higher than conventional speeds as they encounter various sea conditions, which affect their stability and safety. The International Maritime Organization High-Speed Craft 2000 (IMO HSC 2000), where the focus is mainly laid upon the comparative analysis of single-chine and double-chine hull configuration in semi-planning type craft, forms a regulatory background for determination of stability and performance as required out-to-sea. We then compare the practical design space to the requirements of a stability code and identify optimal hull shapes for improved safety and efficiency in high-speed marine operations.

3 Numerical Methods

The flowchart identifies the tasks involved in analyzing the impact of different Chinese choices on the stability of the ship. The process starts with literature collection, which gathers information from various journals, books, and internet sources. Maxsurf software is used to build the shape of the ship’s hull, after which it collaborates to get the best-shaped hull. Finally, hydrostatic data is obtained from the Maxsurf Modeler and adjusted if required. Once an acceptable percent range of the hydrostatic data (±5%) is achieved, single or double chine versions of the hull are inserted. It is then exported to Maxsurf Stability, where load scenarios, the rooms, and requirements set in stability simulation are applied. Finally, the stability findings are looked at to round off the technique.

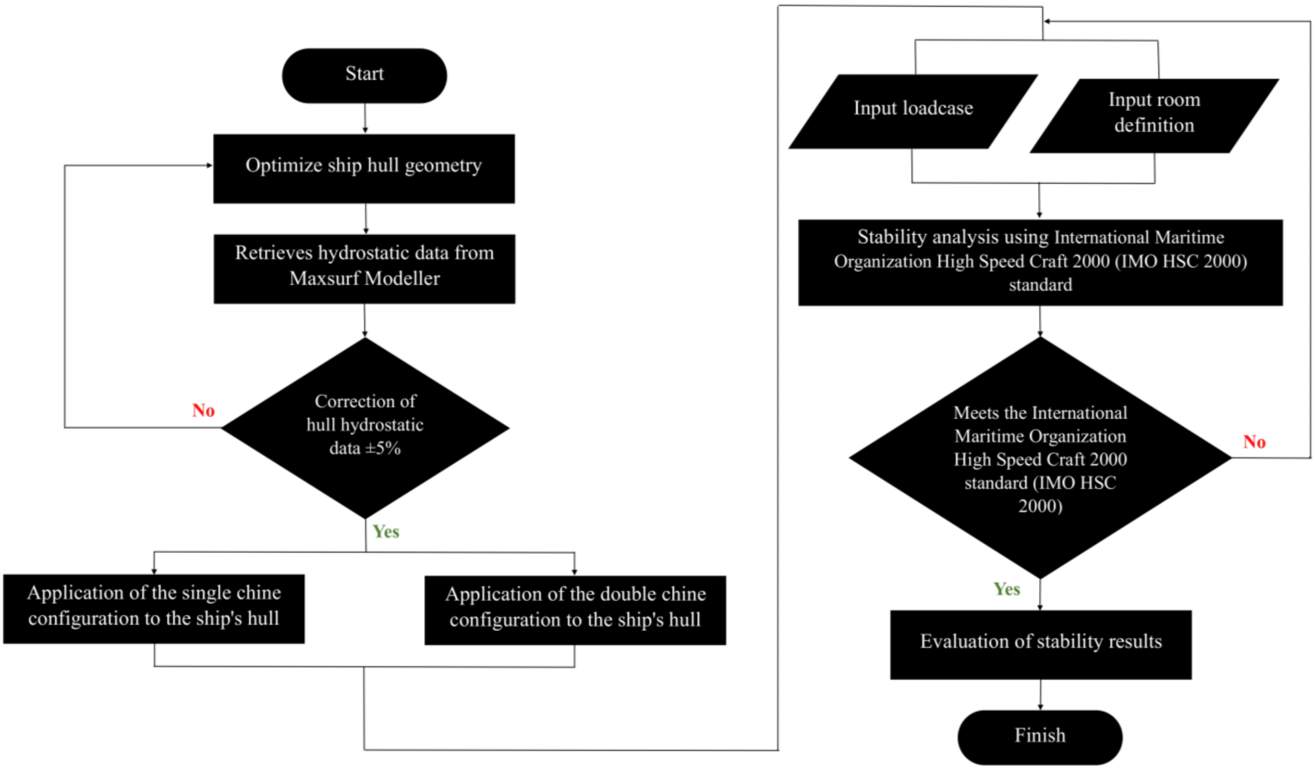


Figure 2. Flowchart of the current methodology

3.1 Reference model design

The reference ship model was produced with Maxsurf software to confirm that it matched the predicted hydrostatic data. Hydrostatic data validation was carried out by comparing the model's calculations to previously reported hydrostatic data, as given in Table 2 [26].

Table 2. Parameter of reference design [26]

Parameter	Trim by Stern (degree)			
	Even Keel	1	2	3
Displacement (ton)	20.19	11.78	6.271	3.979
Volume displaced (m^3)	19.696	11.495	6.118	3.882
Draft amidships (m)	0.45	0.45	0.45	0.45
Immersed depth (m)	0.45	0.45	0.45	0.45
Water Line (WL) length (m)	17.700	17.392	12.953	8.661
Wetted area (m^2)	68.232	57.706	37.794	24.376
Waterplane area (m^2)	62.898	55.231	36.243	23.052
Prismatic coefficient (Cp)	0.835	0.661	0.522	0.95
Block coefficient (Cb)	0.619	0.372	0.286	0.297

Figure 3 depicts a reference hull design, showcasing detailed views such as a body plan, a half-breadth plan, and a 3D perspective of the hull. The body plan reveals vertical cross-sections of the hull at various points along its length, illustrating the changes in hull shape from the front to the back. The half-breadth plan displays horizontal slices of the hull, providing information about its width at different heights above the keel. The 3D perspective visually represents the overall hull shape, emphasizing the sharp chine angles and streamlined form. These plans are essential for comprehending the hydrodynamic characteristics of the hull, as they determine how the hull interacts with water during motion, impacting stability, resistance, and overall performance.

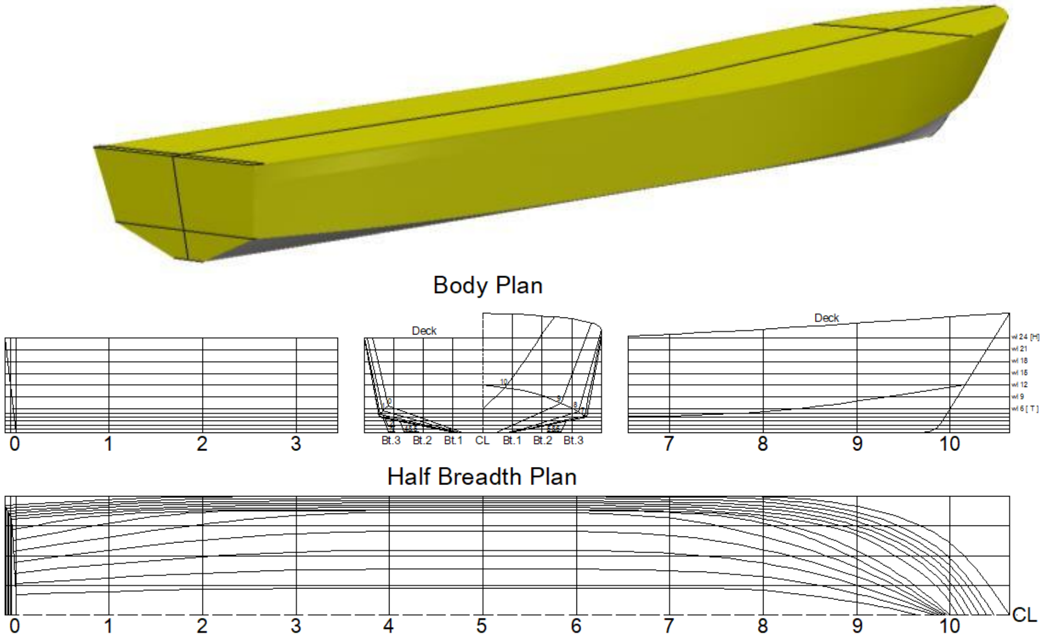


Figure 3. 3D view and lines plan of reference hull design [26]

3.2 Data validation

Corrections were done whenever disparities exceeded ±5% to maintain the model's accuracy within acceptable ranges [30]. Benchmarking results in Table 4 show that the generated ship model closely matches the reference model, with variations of less than ±5%. Table 3 provides a more complete summary of these. The results show that the models have a comparable level, showing that the new one adequately imitates the old one's hydrostatic properties. These minor variances provide a solid foundation for evaluating how alterations such as single and double chine applications influence ship longevity and efficacy, implying that the enhanced version can aid in investigating future improvements.

Table 3. Value details from recent research

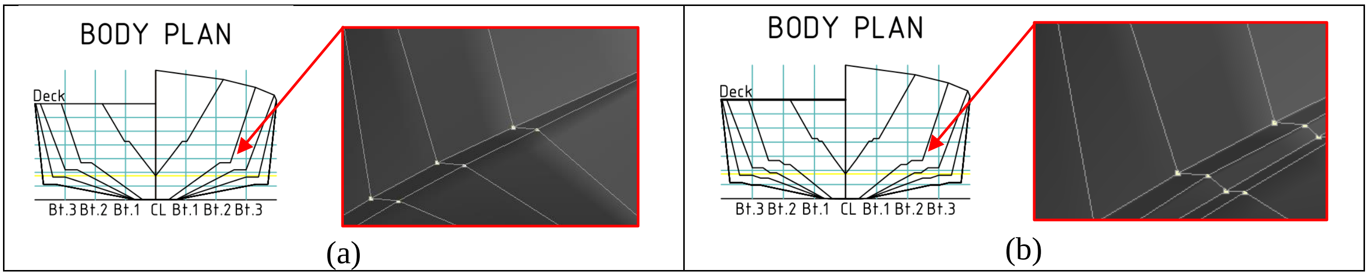
Parameter	**Recent**			
	Trim by Stern (degree)			
	Even Keel	**1**	**2**	**3**
Displacement (ton)	20.16	11.29	6.483	4.176
Volume displaced (m^3)	19.67	11.018	6.325	4.074
Draft amidships (m)	0.45	0.45	0.45	0.45
Immersed depth (m)	0.45	0.45	0.45	0.45
WL length (m)	17.385	17.492	13.058	8.722
Wetted area (m^2)	67.623	55.018	36.139	23.716
Waterplane area (m^2)	62.485	53.395	34.813	22.941
Prismatic coefficient (Cp)	0.806	0.65	0.498	0.914
Block coefficient (Cb)	0.594	0.388	0.301	0.284

Table 4. Correction between the latest study and the reference

Parameter	Correction (%)			
	Trim by Stern (degree)			
	Even Keel	**1**	**2**	**3**
Displacement (ton)	-0.15	-4.34	3.27	4.72
Volume displaced (m³)	-0.13	-4.33	3.27	4.71
Draft amidships (m)	0.00	0.00	0.00	0.00
Immersed depth (m)	0.00	0.00	0.00	0.00
WL length (m)	-1.81	0.57	0.80	0.70
Wetted area (m²)	-0.90	-4.89	-4.58	-2.78
Waterplane area (m²)	-0.66	-3.44	-4.11	-0.48
Prismatic coefficient (Cp)	-3.60	-1.69	-4.82	-3.94
Block coefficient (Cb)	-4.21	4.12	4.98	-4.58

3.3 Single and double chine

Following validation of the reference model, adjustments including single and double chine were implemented according to references, with a chine width of 15 cm [30]. These improvements sought to assess the hull shape's impact on ship resistance and efficiency. Figure 4 shows the ship's body layout and 3D design for Chinese applications, single or double. It is a diagram that depicts structural details and outlines, demonstrating ship shape and hydrodynamic performance. The profile view shows the ship's side elevation, the plan view shows the hull from above, and the body plan shows portions or slices of the hull at regular intervals throughout the ship's length. These combined views assist in measuring the hull's volume distribution, wetted surface area, and overall geometry, which are necessary to evaluate stability.



(a)

(b)

Figure 4. Variation of semi-planning hull ship: (a) Single chine, and (b) Double chine

3.4 Stability simulation

The weight moment was determined for the center gravity point of the semi-planning hull to investigate stability. The Deadweight Tonnage (DWT) of the semi-planning hull contained people, baggage, fuel oil, fuel diesel oil, and freshwater. The Lightweight Tonnage (LWT) then included the overall hull, outboard engine, outfitting component, accommodation equipment, navigation equipment, deck machinery, and life-saving appliances and equipment [26]. The weight distributions of DWT and LWT components followed a standard layout. The weight distributions were then fed into Maxsurf Stability's load case, as shown in Table 5. The stability characteristics were then rectified using the International Maritime Organization High-Speed Craft 2000 (IMO HSC 2000) standards supplied by the Maxsurf Stability program.

Table 5. Stability load case detail

Item Name	Quantity	Unit Mass (ton)	Unit Volume (m^3)	Total Volume (m^3)	Longitudinal Levers	Transverse Levers	Vertical Levers	Total Free Surface Moment (FSM) (ton.m)
Lightship	1	16.494	16.494			9.5	0	0.9
Fuel oil	80%	0.472	0.378	0.5	0.4	4	0	0.7
Fuel diesel oil	80%	0.42	0.336	0.5	0.4	5.25	0	0.7
Fresh water	80%	1	0.8	1	0.8	6.5	0	0.7
Passenger	10	0.085	0.85			8	0	0.9
Navigation	1	0.15	0.15			13.5	0	2.375
Luggage items	1	0.1	0.1			11	0	1.9
Outfitting equipment	1	0.05	0.05			3.5	0	1.9
Accommodation equipment	1	0.05	0.05			5	0	1.75
Deck machinery	1	0.04	0.04			9.5	0	1.75
Lifesaving appliances and equip	1	0.03	0.03			7.5	0	1.75
Total load case			19.278	2	1.6	9.136	0	0.909
FS correction								0.042
Vertical Center of Gravity (VCG) fluid								0.951

4 Results and Discussion

4.1 Single chine configuration

The table shows the stability study findings for a ship's hull with a single chine design at various trim by stern angles: even keel, 1 degree, 2 degrees, and 3 degrees. The ship's trim by stern angle always remains lower than the 16-degree limitation as High-Speed Craft (HSC) 2000 Annex 8 Monohull Intact regulations, so the rules of the Weather Criterion are met. The Steady Heel/Margin Line Immersion Angle must be less than 80 degrees, with values ranging from 3.28 to 4.29. The stability, as evaluated by the area under the GZ curve for Areas 0 to 30 degrees and 30 to 40 degrees, decreases as the heeling angle increases but stays within acceptable bounds. Moreover, as Plot 3 depicts, the Maximum GZ at 30 degrees, or more excellent criterion, and the Angle of Maximum of GZ slightly increase with the trim angle, testifying to the hull's stable ability to regain stability when overhauled. When the initial GMt based on metacentric height is calculated, and the value 1.6 is obtained, it is observed that the GMt slightly decreases as additional trim angles are simulated while remaining above the minimum acceptable level of 0.15 as an ideal first stability value. In general, the single chine configuration is relatively stable under the conditions above, as seen in Table 6, wherein all the stability criteria are stroked at several degrees of trim by stern angles.

Table 6. Stability of single chine configuration

Code	Criteria	Value	Stability of Single Chine Configuration				Status
			Even Keel	1 degree	2 degrees	3 degrees	
HSC 2000 Annex 8 Monohull Intact	1.1 Weather criterion from IMO A.749(18) Angle of steady heel shall not be greater thank (<=)	16	1.2	1.4	1.1	1.3	Pass
	The angle of steady heel/Margin line immersion angle shall be less than (<)	80	3.41	4.29	3.28	3.91	Pass
	1.2 Area 0 to 30 or Maximum GZ	3.15	16.801	14.7447	21.7957	17.5747	Pass
	1.3 Area 30 to 40	1.71	8.8125	8.5979	13.8926	10.7309	Pass
	1.4 Maximum GZ at 30 or greater	0.2	0.907	0.915	1.686	1.172	Pass
	1.5 Angle of maximum GZ	15	42.7	48.2	57.3	51.8	Pass
	1.6 Initial GMt	0.15	3.677	2.594	3.466	3.061	Pass

4.2 Double chine configuration

The table displays the stability research results for a ship's hull with a double chine configuration, evaluated at various trim by stern angles: even keel, 1 degree, 2 degrees, and 3 degrees. The configurations are adjusted according to the High-Speed Craft (HSC) 2000 Annex 8 Monohull Intact, in which the maximum ship's heel angle does not exceed 16 degrees based on the Weather Criterion. The space for the Angle of Steady Heel/Margin Line Immersion Angle less than 80 degrees is also fulfilled, with such values as 3.25 to 4.23 degrees. The stability of the GZ curve area for Area 0 to 30 degrees and Area 30 to 40 degrees proves the strong initial stability, particularly for the 2-degree tilt, which remains close to the acceptable limits. Further, the Maximum GZ at 30 degrees or greater and the Angle of Maximum GZ criteria reveal the hull's ability to recover from greater heel angles with slight increases in the corresponding GZ values as the heeling angle increases. The initial GMt values show the metacentric height, which reduced slightly as the degree of heel increased. However, they are more significant than the benchmark of 0.15, which is reasonably satisfactory, which means there is initial stability during the creation of added value. Thus, it can be stated that the double chine configuration demonstrates relatively stable behavior for the specified conditions and complies with the stability criteria presented in Table 7 when the vessel is heeled.

Table 7. Stability of double chine configuration

Code	Criteria	Value	Stability of Double Chine Configuration				Status
			Even Keel	1 degree	2 degrees	3 degrees	
HSC 2000 Annex 8 Monohull Intact	1.1 Weather criterion from IMO A.749(18) Angle of steady heel shall not be greater thank (<=)	16	1.2	1.4	1.1	1.3	Pass
	The angle of steady heel/Margin line immersion angle shall be less than (<)	80	3.38	4.23	3.25	3.94	Pass
	1.2 Area 0 to 30 or Maximum GZ	3.15	16.844	14.7833	21.8818	17.4718	Pass
	1.3 Area 30 to 40	1.71	8.8507	8.6295	13.9415	10.5904	Pass
	1.4 Maximum GZ at 30 or greater	0.2	0.913	0.919	1.692	1.181	Pass
	1.5 Angle of maximum GZ	15	43.6	48.2	57.3	51.8	Pass
	1.6 Initial GMt	0.15	3.708	2.613	3.489	3.103	Pass

4.3 Righting levers analysis result

Figure 5 compares the maximum GZ (righting levers) values for single and double chine designs for the following trim by stern angles: 0 degrees or level, 1 degree, 2 degrees, and 3 degrees off an even keel. The double-chine configuration yields greater GZ values than the single-chine configuration from the graph; this is particularly evident at the 2 degrees trimmed by the stern angle, which shows the most significant disparity in GZ values to mean that the double-chine configuration is more stable.

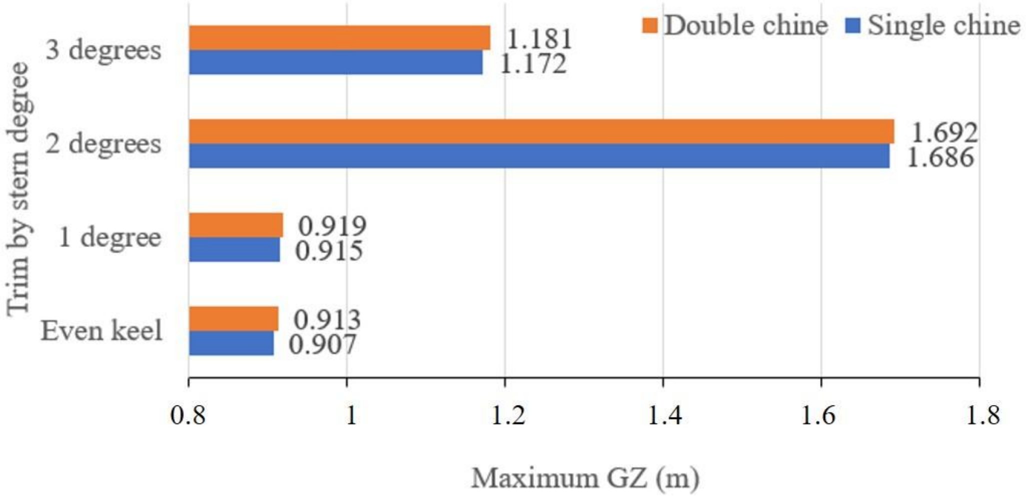


Figure 5. Maximum GZ value based on different trim conditions

Table 8 demonstrates that the double chine hull structure has higher GZ values than the single chine form, especially at larger heel angles. For a heel angle of 20 degrees, the double chine arrangement at 2 degrees yields a GZ value of 0.96 meters, slightly higher than the single chine configuration at 0.957 meters. At a heel angle of 40 degrees, the GZ value for the double chine configuration is 1.516 meters, compared to 1.510 meters for the single chine. More substantial differences may be noticed at heel angles of 60 and 80 degrees, where the double chine design produces GZ values of 1.689 and 1.486 meters, respectively, as opposed to 1.683 and 1.482 meters for the single chine. In these conditions, the double chine arrangement regularly outperforms, demonstrating a more remarkable ability to restore the vessel to its previous position following external forces such as waves and wind disruption.

Table 8. Righting levers of the semi-planning hull with chine configurations in the stability range of each stern trim condition

Model	Heel Degree	Righting Levers GZ (m)									
		0	**20**	**40**	**60**	**80**	**100**	**120**	**140**	**160**	**180**
Single Chine Configuration	Even Keel	0	0.724	0.907	0.792	0.431	-0.032	-0.484	-0.81	-0.927	0
	1 Degree	0	0.643	0.915	0.879	0.567	0.142	-0.293	-0.655	-0.843	0
	2 Degrees	0	0.957	1.510	1.683	1.482	1.059	0.514	-0.058	-0.527	0
	3 Degrees	0	0.754	1.131	1.172	0.893	0.459	-0.026	-0.463	-0.746	0
Double Chine Configuration	Even Keel	0	0.724	0.913	0.799	0.435	-0.031	-0.484	-0.81	-0.928	0
	1 Degree	0	0.643	0.919	0.885	0.571	0.144	-0.293	-0.655	-0.843	0
	2 Degrees	0	0.96	1.516	1.689	1.486	1.061	0.514	-0.058	-0.527	0
	3 Degrees	0	0.758	1.141	1.181	0.898	0.459	-0.026	-0.464	-0.746	0

5 Conclusions

The stability analysis of semi-planning hulls with single and double chine configurations indicates that both designs match the essential parameters effectively. For the weather criterion based on International Maritime Organization (IMO) A.749(18), both designs maintained the angle of constant heel far below the 16-degree restriction, with the single chine and double chine configurations registering angles between 1.1 to 1.4 degrees, which is just 6.88% to 8.75% of the permitted limit. The margin line immersion angles for both configurations also performed well, staying significantly below the 80-degree threshold, with the single chine at 3.28 to 4.29 degrees (4.10% to 5.36% of the limit) and the double chine at 3.25 to 4.23 degrees (4.06% to 5.29% of the limit). Additionally, both designs' areas under the GZ curve (0 to 30 degrees) demonstrated outstanding stability, with values that guarantee safe operation under various heel angles. These results confirm that the double chine configuration has ever so slightly enhanced stability when performing the trim by stern angle test, which may thus be more beneficial in improving the ship's stability. Further studies should concern other factors that contribute to stability, such as various types of hulls, states of loading, and the effects of waves and wind. Further improvements in hull shape and stability may be made if more Chinese configurations and advanced simulation tools are used, as well as actual hull model tests or ship models.

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