Empirical Feasibility Study to Design and Build Rigid Hull Inflatable Boat for Special Operation Units in Sri Lanka Navy

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Abstract— *Sri Lanka is an Island nation and with its geopolitical situation, safeguarding national interest entrusted with the country's naval force. Effective surveillance and search in territorial waters become paramount to deny such threats. United Nations Office for Drugs and Crimes under its Global Maritime Crime Programme in the South Asian region has indicated the feasibility to fund a project, if the Navy is capable of design and build the required boats. The authors being the naval architects in the Navy conducted an empirical feasibility study to understand and solve the critical success parameters to design and build the required boat. This study incorporates (a) to estimate the boat's total hull resistance at the specified maximum speed, (b) to estimate the total propulsive power and select the propulsion power package to achieve the maximum speed, (c) to optimize the RHIB dimensional parameters, the centre of weight to improve performance and stability, and (d) to determine the fulfilment of intact stability criteria of the design. The total hull resistance at light running condition was 7.1 Kn. The Mercury diesel Bravo sterndrive unit with model number 4.2 (nominal power 350hp @ 3800RPM) was selected as the most suited power package for this application. The length overall and the amidships beam were 7.5 meters and 3.0 meters respectively. The boat is capable of a range of 55 NM, and a maximum speed of 34 Knots. The intact stability fulfils the IMO Intact Stability Code requirements.*

Keywords— **Intact stability, propulsive power, total hull resistance**

I. INTRODUCTION

Sri Lanka is an Island nation and with its geopolitical situation, safeguarding national interest is comprehensively entrusted with the country's naval force. The foremost interests are the sea-born threats, which make inroads into the nation. Effective surveillance and search in territorial waters (0-12 nautical miles from land) becomes paramount to deny such threats. The self-designed Visit Board Search and Seizure (VBSS) operations have given good results in the past and now need to uplift the operations to mitigate intruders' strategies. United States Navy donated the Rigid Hull Inflatable Boats (RHIB) during the year 2000, currently used by the Navy and at present boats are at the end of their life cycle. Due foreign currency crisis of GoSL, the navy could not afford to purchase the required boats and neither any nation is to donate RHIB in the near future. However, the United Nations Office for Drugs and Crimes (UNODC) under its Global Maritime Crime Programme (GMCP) in the South Asian region, with its main objective to minimize illegal activities (human smuggling, drug trafficking, and piracy) has indicated the feasibility to fund a project, if Navy is capable of design and build the RHIB. The Naval Boat Building Yard (NBBY) was established in the year 2000 at Welisara Naval Complex to custom-build Glass Reinforced Plastic (GRP) boats with local consultants.

The Ministry of Development Strategies and International Trade has developed the National Export Strategy of Sri Lanka recognizing the changing paradigm in international trade. Thereby the country needs to diversify its product basket with new and innovative products to suit the fast changing pattern. In this context the boat building process of the Sri Lanka Navy involves an inclusive and collaborative approach, engaging both public and private sector participants. To unlock its full potential, Sri Lanka Navy has capitalized on key prospects in manufacturing and establishing synergies with other sectors, ensuring the seamless fulfilment of the entire boating value chain. Over the years the institute has developed its own capacities in design features and during the year 2018/2020 NBBY exported military boats to Nigeria and Seychelles.

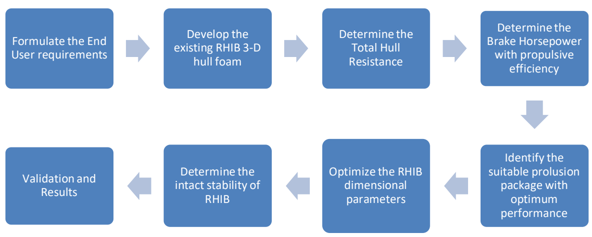
A. Research Problem and Significance

The authors being the naval architects at NBBY conducted a feasibility study to design and build the required RHIB for special operation units in the Navy. Thus, the research problem is, to understand and solve the critical success parameters leading to the design and build a low-cost RHIB as per navy special operation units requirements by the NBBY. Since the novel propulsion package is required to be selected and since the maximum speed requirement of the end-user is different from the existing design (doated boats), calculations are required to ensure stability, resistance cum powering, and performance of the modified boat.

B. Research Objectives and Future Studies

The objectives of this research paper are limited (a) To estimate the RHIB total hull resistance at the customer specified maximum speed, (b) To estimate the total propulsive power and select the propulsion power package the boat desires to achieve the maximum speed, (c) To optimize the RHIB dimensional parameters, the centre of weight to improve performance and stability, and (d) To determine the fulfilment of intact stability criteria of the design. The authors will also discuss the GRP structure design of RHIB, manoeuvrability features, manufacturing cost, and life cycle management during the subsequent research paper.

II. Research Methodology



III. Development of the Design, Results and Discussion

A. Formulate the End User Requirements

The RHIB is to be with a solid single rigid hull with a flexible inflatable tube at the gunwale and to be capable of operation up to sea state 2 and with survival at sea state 3. The preferable length overall and amidships beam with 7.5 meters and 3.0 meters respectively. Total human capacity 12, range of 50 NM, and a maximum speed of 35 Knots. Inflatable tube construction with Polyurethane coated nylon. As per the customer, the propulsor is to be a sterndrive considering past experience on superior manoeuvrability with less vibration/sound (communication ease at open sea) and as the engine cum sterndrive housed at the stern it allows more space for VBSS operations at forecastle area.

The sterndrives are proven more cost effective (acquisition, maintenance, and fuel efficiency) than the outboard engines and outperform outboard engines in calm water. Although the inboards are proven to have better performance in rough water conditions, authors determined that most operations would be conducted in the coastal waters and the sea states would not be greater than 2 in these conditions. When compared with the inboards the sterndrives have the advantage of being more improved visibility at the stern, and increased interior space. The latter two factors are important for the end-user considering the operation. Thus, it was determined that the sterndrive was the better option when compared with the outboard and inboard engines.

B. Develop the Existing RHIB 3-D Hull Form

As an initial step of this process, the 3-D hull model was developed using the Rhinoceros 3D software using the existing Lines Plans of the RHIB. The hull was developed using control point manipulation, ensuring the curvature of the hull is preserved. The load condition of the RHIB was determined after developing the hull.

A detailed weight estimation was conducted, considering all the weights related to the hull, machinery, equipment, and deadweight loads. Additionally, the calculation of the center of gravity was performed. The hull shape and the newly estimated center of gravity of the RHIB were utilized in Orca3D software to establish the initial drafts and trim angle. Subsequently, NavCad software was employed to conduct the resistance and propulsive analysis mentioned in the methodology.

C. Determine the Total Hull Resistance

The best option to calculate the total hull resistance (viscous/friction, wave making, and air) with a particular hull shape was by conducting a towing tank test, yet it involved enormous work/ money (Lindbergh and Ahlsrand 2020). The towing tank facilities are not available in Sri Lanka and the cost-benefit of conducting a towing tank test at an overseas facility is not justifiable for this project. Hence, the next best option is to employ a parametric hull resistance prediction software with a library with an extensive data repository (Lindbergh and Ahlsrand 2020; Islam et al. 2022; Understanding NavCad's place, n.d.).

In addition, total hull resistance includes several other minor resistance components such as (a) appendage resistance (depends on the Froude number, surface area, and location) and steering resistance, (b) wind and current resistance, (c) added resistance due to waves, and (d) increase resistance in shallow water (ITTC Recommended procedures and guidelines 2021; Susanto et al. 2017). However, the above are occasional resistance components and need not be considered for engine powering calculations. Since the customer, specified maximum speed is required to be achieved in calm water, and calm air conditions, as discussed in their studies the appendage resistance will not exceed more than 5% once the ship/craft reaches planning hull states i.e., Froude number greater than 1.2 (John et al. 2012).

Classification based on the Froude number (Fn) of a hull is one of the most important factors when studying the resistance and powering of a ship/craft. The Froude number for a ship/craft is calculated using the eq. (1) (Lindbergh and Ahlsrand 2020).

$$F_n = \frac{V}{\sqrt{g.L_{WL}}} \quad (1)$$

Where,
Fn: Froude Number (Dimensionless), V: Velocity of the craft (ms^{-1}), g: Gravitational acceleration (ms^{-2}), LWL: Length on waterline (meter)

The Froude Number calculated for the proposed RHIB was 1.61 (V= 18.01 ms^{-1}, LWL = 6.2 m), thus RHIB was considered as a planing hull, at the maximum design speed for the purpose of input data to estimate the hull resistance with NavCad software.

In this study, the authors selected NavCad software, which is one of the leading resistance prediction software in the naval architecture field to estimate the total hull resistance and the propulsion power of the RHIB. This software is suitable to estimate resistance and power requirements of vessels ranging from large displacement ships to fast planning craft with any form of mono hull to multihull ship/craft. NavCad is based on a collection of empirical methods with its data repository. The resistance prediction methodologies are the most established and contemporary resistance prediction methods developed by naval architects over the years. The software is created by HydroComp and is constantly updated to keep up with the industry requirements.

Based on the above, the following conditions were established to determine the total hull resistance;

i. Light running condition – 0 year clean hull, Sea State 0, Appendage Resistance 5
ii. Most probable/design running condition - 1 year old rough hull, Sea State 2 (expected operation), Appendage Resistance 5
iii. Heavy running condition - 5 year old rough hull (towing, due to heavy seaway, fouled hull condition etc.), Sea State 3 (survival), Appendage Resistance 5

Out of the three conditions, the authors mainly considered the light running condition when achieving the customer requirement of a maximum speed of 35 knots. However, the authors also considered how the performance of the RHIB would be as the hull condition deteriorates to provide customer with useful input on the requirement of hull maintenance.

The authors input the 3-D hull form developed using the Rhinoceros 3D software to the NavCad software, and the Savitsky method was selected by authors as the most suitable resistance and hull propulsor interaction prediction method (Table 1) to the NavCad, based on the relevancy of input data.

Table 1: Savitsky method parametric comparison with RHIB data

Parameter	SAVITSKY range	RHIB design value
FNB DESIGN	0.06 – 13.00	1.61
XCG/BPX	0.60 – 3.00	1.33
Deadrise (deg)	0.00 – 30.00	19.8

Where;
FNB Design: Froude Number based on Chine Beam, XCG/BPX: Longitudinal Center of Gravity from Transom to Chine Beam Ratio, Deadrise angle: Transverse angle of the effective slope of the planning bottom, measured against the horizontal.

Further, enclosure 1 contains the initial input data for NavCad software to determine the total hull resistance of RHIB. The complete report generated with NavCad software is attached as enclosure 2 to this paper. The total hull resistance (RTOTAL, in kN) developed using NavCad for the light running condition is depicted in Figure 1 below. Figure 2 depicts the total effective power (PETOTAL, in hp) estimation for the light running condition.

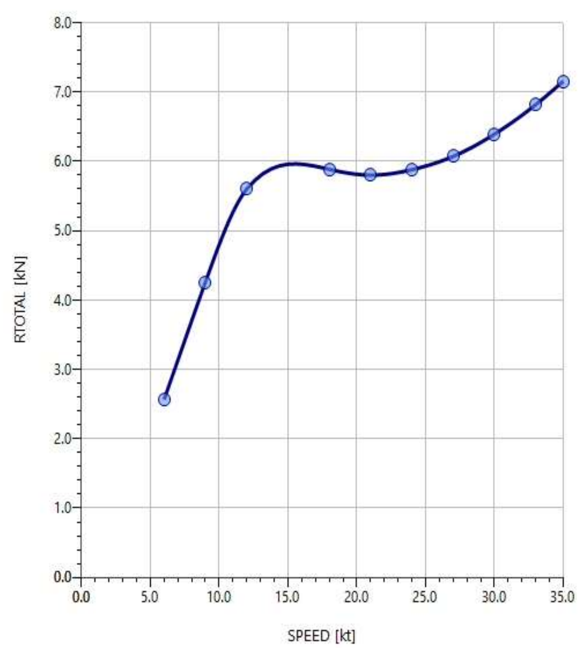


Figure 1. RHIB total hull resistance estimation for light running condition

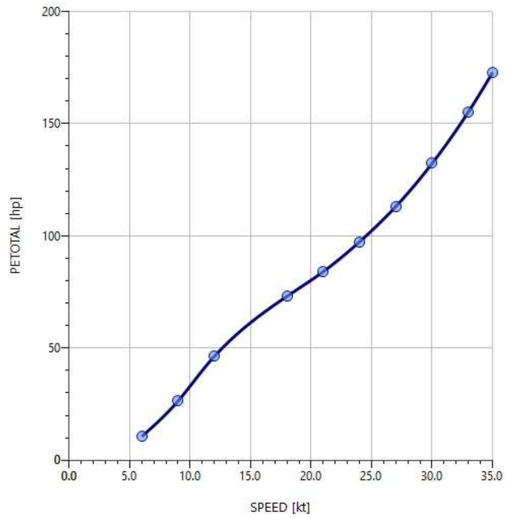


Figure 2. RHIB total effective power estimation for light running condition

Table 2: RHIB Performance details for narrated running conditions

Condition	Craft Speed (Knots)	Total Resistance (kN)	Effective Horse Power (EHP)
Light running condition	35	7.1	174
Most probable running condition	35	8.5	203
Heavy running condition	35	10.2	243

The next step is to determine the hull efficiency. The engines deliver the total power required to propel the craft. As defined by Stapersma and Woud (2005) the engine power requirement further depends on the hull efficiency and the hull efficiency can be defined as eq. (2). The ratio of the two is a measure of how effectively the shape of the stern has been designed to suit the propulsion arrangement.

$$\eta_H = \frac{P_E}{P_T} \tag{2}$$

Where; η_H = Hull efficiency, P_E = Effective horse power, and P_T = Thrust horse power

The hull efficiency of a boat is a measure of how well the shape of the stern reduces drag and allows the craft to move through the water more efficiently (Zubaly 1996). For the proposed RHIB, Hull efficiency was 0.98 (as per the NavCad software). Thus, the Thrust horsepower at light running condition is approximately 177.5 hp. Thus, the first objective of the paper is achieved.

D. Determine the Brake Horsepower with Propulsive Efficiency

The proposed arrangement of the power unit is depicted in Figure 3. Susanto et al. (2017) discussed, a propulsion system onboard a boat/ship is to convert fuel energy into useful thrust to propel the ship in the following sequence. Brake Horsepower (BHP), Shaft Horsepower (SHP), Thrust Horsepower (THP), Delivered Horsepower (DHP), and the Effective Horsepower (EHP). Figure 4 depicts a simplified ship drive train with efficiencies.

The sterndrives in the market are with engine specifications; thereby authors need to estimate approximate BHP to identify a candidate propulsion package. The proposed RHIB is with single engine application and directly coupled to the sterndrive. The authors found in-built reduction gear ratio of candidate packages is around 1.5: 1.

Figure 3. Main engine with a sterndrive (Boatbuy, 2023)

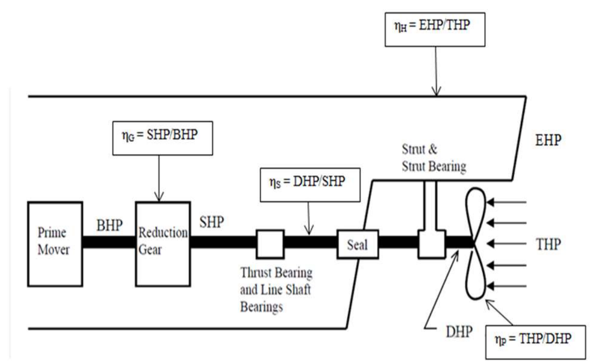


Figure 4. Simplified ship drive train with efficiencies (USNAOE 2023, p.10)

The relationship between DHP and THP could be defined as follows (Susanto et al. 2017; Danian 2017). THP is considerably smaller than DHP (Danian 2017) due to inefficiencies in converting the propeller's rotational motion into linear thrust.

The authors followed the below steps to determine the propulsion efficiency of the sterndrive unit with a similar type of available RHIB.

i. Trial conducted immediately after the routine underwater maintenance
ii. Trials conducted with a major overhauled engine

iii. Trials conducted with the designed load conditions to ensure the correct water plan area
iv. Trial conducted with a cleaned propulsion unit

With the above depicted approach, authors observed boats driven by sterndrive propulsion systems display a propulsion efficiency of around 50%. For this study, the authors decided to use 50% as the efficiency value since calculations using the upper range efficiency would not leave an allowance.

Danian (2017) discusses drive shaft efficiency as the ratio between the thrust power and delivered power and the typical value as 97% to 98%.

The efficiency of the Propulsion System = THP / BHP
Since the sterndrive system is a package, the authors estimated BHP as, BHP = 177.5 hp/50%
(propeller efficiency, reduction gear efficiency, and shaft efficiency) = 355 hp

As per the above estimation at the light running condition, the RHIB requires a propulsion package (engine cum sterndrive) with a BHP of approx. 350hp to achieve the maximum speed requirement of 35 knots.

E. Identify the Suitable Propulsion Package with Optimum Performance

However, further analysis is required to validate the engine-propeller interaction and ensure that the selected combination could achieve the maximum speed and analyze their behaviour as the condition of the hull deteriorates.

Van Uy (2016) in his paper discuss the energy unbalance between main engines and propellers. The unbalance makes boats/ships' operation costs rise as it consumes more fuel. The unbalanced energy is mainly developed by shape deformation of ships' hull/ propellers, and marine growth leading to over torque or torque-rich operation. Thus, reducing the main engine operating envelope and limit the harness of full power at the designed RPM. Further, Van Uy (2016) discuss that similar features could exist with an incorrect match, an engine with an existing propulsor unit, which leads to operate in torque-rich condition.

As discussed by Stapersma and Woud (2005) in their studies, the selection of a craft/ship propulsion system and the correct matching of the engine to the propulsor will not alone solve the entire concern but need to consider the variation in the total hull resistance (off design operation). The propulsion system may not only operate satisfactorily in the design condition of the boat, but also in off-design situations (variations in craft displacement, added resistance caused by a seaway, impact of driving engines, fouled hull, and active propulsors, etc.,) which the boat might encounter.

The authors were meticulous about the above phenomenon while optimizing the propulsion units. Thus, ensured;

i. The engine is able to develop full power, or nearly full power, at the design condition.
ii. The propulsion plant functions satisfactorily in all design and off-design conditions, without exceeding any limits imposed by the operational envelope.
iii. The operation of the propulsion plant is optimized with regard to fuel consumption (i.e., the power absorber is close to the engine MCR curve)

The authors surveyed the international shelf for suitable propulsion sterndrive units for this application and found the Mercury diesel Bravo sterndrive unit with model number 4.2 as the most suited unit for this application. The basic specifications are intermittent rating, In line diesel, and nominal power 350hp @ 3800RPM.

Minbox (2020) in his studies, proposes selecting an engine for a propulsor need to consider the propeller curve with a standard engine load diagram. Thus, the authors develop the power (PBENG, in hp) RPM curve for light condition running as depicted in Figure 5. The figure ensures propulsion plant functions at a satisfactory level in all design (nearly hitting the corner) and off-design conditions (have sufficient acceleration reserve), without exceeding any limits imposed by the operational envelope. The detailed report is attached as enclosure 3 to this paper. Further, fuel efficiency was found to be reasonable as per details depicted in Table 3.

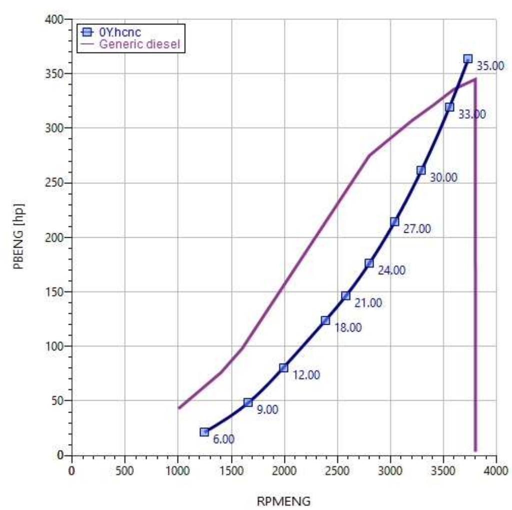


Figure 5. Main engine cum sterndrive propeller demand

As per the above Figure 5, it is observed that with the selected propulsion package the RHIB could achieve a maximum speed of 34 knots and in the process, it is hitting the corner at a satisfactory level.

Table 3. Selected main engine specific fuel consumption table

Sr. No.	RPM	Power (kW)	Fuel consumption (l/hr)	Fuel consumption (g/hr)	SFC (g/kWh)
01	1000	32	2.7	2265.03	70.78
02	1400	57	3.8	3187.82	55.92
03	1600	73	7.4	6207.86	85.04
04	2000	118	12.2	10234.58	86.73
05	2400	169	19.1	16022.99	94.81
06	2600	192	23.8	19965.82	103.99
07	2800	205	28.6	23992.54	117.04
08	3000	217	34.7	29109.83	134.14
09	3200	229	41.9	35149.91	153.50
10	3400	240	52.6	44126.14	183.86
11	3600	250	62.9	52766.81	211.07
12	3800	257	81.4	68286.46	256.71

The power package is equipped with a gear ratio and propeller that allows the engine to operate at wide-open throttle (WOT)
at the engine's rated speed (RPM). At the maximum speed, it was observed that 114 litres of fuel are required to achieve the customer required endurance of 50 NM at 34 knots. Thus, the second objective of the paper is achieved.

F. Optimize the RHIB Dimensional Parameters

To optimize a boat's performance need to consider variables such as speed and displacement, length and beam, deadrise angle and Longitudinal Center of Gravity (LCG). For the proposed RHIB speed to be fixed (customer requirement), displacement of the bear hull is to be maintained as designed values when the hull structure is designed and subsequent construction (not in the scope of this article), also deadweights are been suitably selected.

A high deadrise angle diminishes the lift power, consequently leading to a rise in the wetted surface area and greater resistance. Thus, it is preferable to have a smaller deadrise angle to reduce resistance. However, decreasing the deadrise angle comes with the drawback of intensified slamming, which is unfavourable. Hence, when designing a hull, finding a suitable deadrise involves striking a balance between resistance and slamming forces. With the authors' experience in qualitative parameters as maneuverability, seakeeping, mission feasibility, etc. selected a deadrise angle to be within 17 – 20 degrees where the speed and comfort of the ride are optimally managed.

To optimize the RHIB dimensional parameters, i.e. the centre of weight, length, breadth, etc. in order to improve craft performance, various combinations were considered using the same methodology. The craft size was scaled up by factors of 1.2 and 1.5 to estimate the performance of the RHIB from both propulsion and dynamic stability perspective. The boat was not scaled down since the accommodation of the 12 crew members would not be possible if the dimensions were reduced. In both these conditions, the EHP requirement was calculated with NavCad software and observed to increase by 22 % and 37 % respectively. Thus, the present size is considered to be the most optimal size for the design.

LCG is representing the boat's center of gravity along its length, and influences the trim angle i.e. an essential factor in determining the angle between the hull and the water surface. The trim angle impacts the wetted surface and subsequently affects the resistance encountered. In this design, the RHIB had an initial LCG of 2.7 m from the transom based on the weight distribution. Thus, several LCG options were considered to estimate the effect on the craft performance with NavCad software. It was observed that the craft's dynamic stability becomes compromised when the LCG is moved further aft (less than 2.7 m from the transom) and the performance of the craft becomes deteriorated when the LCG is moved forward (more than 3.1m from the transom). Based on the above observation an LCG of 2.9 m was selected to be the most optimal for the RHIB. The improvement is depicted in Figure 6. Thus, the third objective of the paper is achieved.

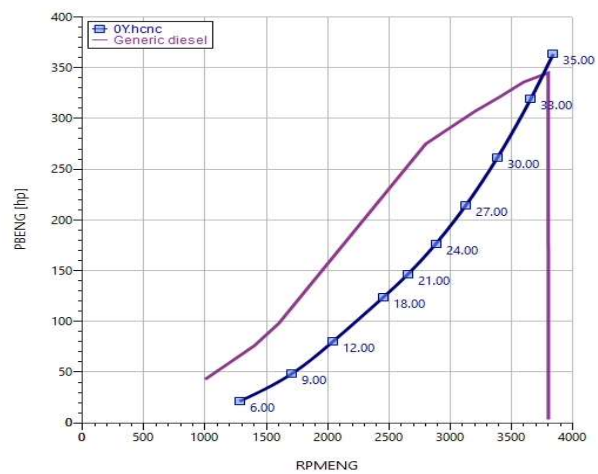


Figure 6. Main engine cum sterndrive propeller demand with optimization

G. The Intact Stability Assessment of the RHIB

Intact stability assessment is crucial for small boats to mitigate risks and ensure the safety of passengers and crew. Conducting such assessments involves a systematic evaluation of a boat's ability to resist capsizing and maintain stability under various conditions. Key factors considered during the assessment include the boat's metacentric height, the center of gravity, hull form, weight distribution, and the effects of external forces.

Both theoretical calculations and practical tests are employed to determine the boat's stability characteristics. The assessment provides valuable insights into potential risks and helps identify necessary modifications to enhance stability, adjust weight distribution, or alter the hull design. By conducting intact stability assessments, designers, regulators, and operators can work together to promote safer small boat operations and prevent accidents caused by instability. For the proposed RHIB the Intact Stability was assessed using the IMO Intact Stability Code requirements. The relevant standard is depicted in Figure 7 as follows.

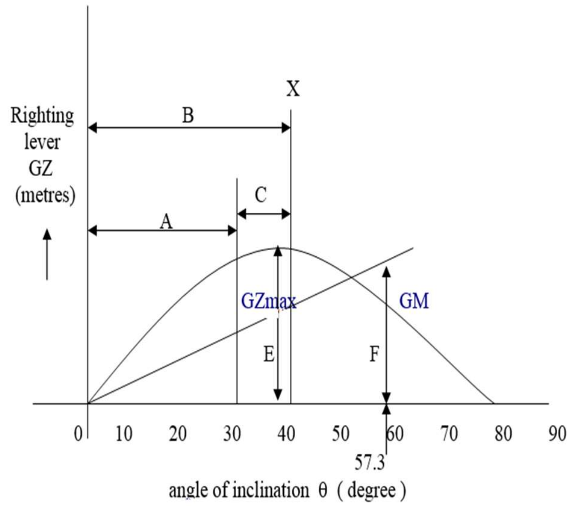


Figure 7. IMO Intact Stability Criteria (Crewtraffic, 2023)

The area under the curve of righting levers (GZ Curve) shall not be less than:

A. Up to an angle of 30 degrees: 0.055 meter radians
B. Up to an angle of X degrees: 0.090 meter radians
C. Between 30 degrees and X degrees:0.030 meter radians
X. 40 degrees or the angle at which the lower edges of any openings in the Hull, Superstructures, or Deckhouses, being openings, which cannot be closed weathertight would be immersed. (Down flooding Angle).
E. a. The righting lever (GZ) shall be at least 0.2 meter (0.66 foot) at an angle of heel equal to or greater than 30 degrees.
b. The maximum righting lever (GZ) shall occur at an angle of heel of not less than 25 degrees.
F. Initial transverse metacentric height (GM) shall not be less than 0.35 meter (1.15 feet)
Note: The tangent of curve at the origin is equal to the line connected between the origin and M at 57.3 deg. (1.0 radian).

The authors used the 3D hull developed as an input in the Orca 3D plug-in software to develop a static stability curve and compared the curve against the IMO standards mentioned above. A summary of this comparison is indicated below in Table 4, showing that the craft passes the stability criteria. Thus, the fourth objective of the paper is achieved. The GZ curve is depicted in Figure 8 as follows.

H. Validation and Results
The authors have fulfilled all intended objectives of the study. However, the authors assumed a few parameters, which were unknown at initial design and need to assume realistic values to progress the study. Table 5 depicts a summary of all assumptions and validity of the same on completion of the project.

Table 4. Intact Stability Criteria Summary

Limits	Min.	Actual	Condition
Area Under GZ between 0.00 and 30.0 deg. (m. rads)	0.055	0.13	Pass
Area Under GZ between 0.00 and 40.0 deg. (m. rads)	0.090	0.20	Pass
Area Under GZ between 30.00 and 40.0 deg. (m. rads)	0.033	0.07	Pass
Maximum GZ (metres.)	0.200	0.5	Pass
Angle of heel at which maximum GZ occur (Deg.)	30	34	Pass
GM fluid (Upright) (metres)	0.150	0.84	Pass

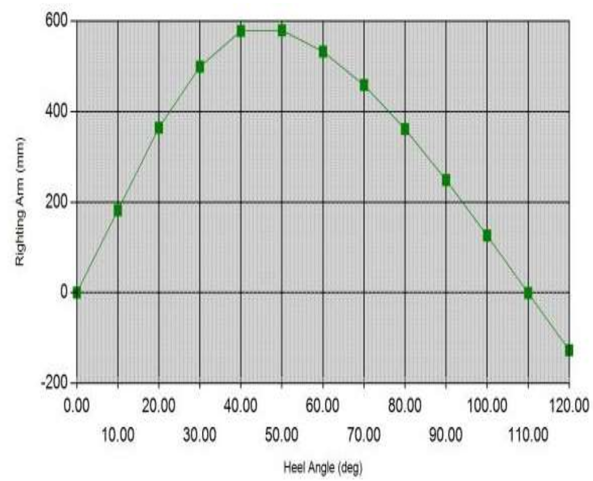


Figure 8. GZ Curve

Table 5. Optimizing of Customer Requirements/ Initial Design Values

Sr. No.	Customer requirement/ initial design values	Optimize/ finalize parameters	Remarks
1.	Maximum speed - 35 Knots	34 Knots	With all possible optimizations
2.	The deadrise angle	20 deg	The deadrise angle selected is optimal with NavCad
3.	Estimated LCG – 2.7 m	2.9 m	LCG optimized for dynamic stability and performance with NavCad
4.	Propulsion efficiency estimation – 50%	50%	Subsequent data of RHIB sea trial
5.	Craft weight estimation – 3.0 tons	3.05 tons	Weight estimation by industrial scale

IV. CONCLUSION

The authors being the naval architects at NBBY conducted a feasibility study to understand and solve the critical success parameters leading to the design and build a RHIB for special operation units in the Navy. The total hull resistance at light running condition was 7.1 Kn. The Mercury diesel Bravo sterndrive unit with model number 4.2 (nominal power 350hp @ 3800RPM) was the most suited unit for this application. The authors were able to design the RHIB, which was capable of operation up to sea state 2, and with survival at sea state 3. The authors selected a deadrise angle to be 20 degrees at transom where the speed and comfort of the ride were optimally managed. The length overall and the amidships beam was

7.34 meters and 2.7 meters respectively. Total human capacity 12, range of 55NM, and a maximum speed of 34 Knots. Further, determined the centre of weight (LCG of 2.9 m) to improve performance and intact stability was assessed using the IMO Intact Stability Code requirements.

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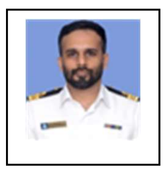

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