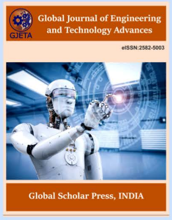
Global Journal of Engineering and Technology Advances

eISSN: 2582-5003

Cross Ref DOI: 10.30574/gjeta

Journal homepage: https://gjeta.com/



(Research Article)

Numerical simulation of intact stability analysis of a catamaran vessel

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Global Journal of Engineering and Technology Advances, 2024, 21(02), 007–022

Publication history: Received on 19 June 2024; revised on 27 October 2024; accepted on 30 October 2024

Article DOI: https://doi.org/10.30574/gjeta.2024.21.2.0138

Abstract

This research work shows the intact stability analysis of a passenger catamaran vessel considering their different load cases: Fully loaded ship to maximum free-board draught; lightship with full tanks; and lightship with no passengers, crew, and empty tanks. The MAXSURF package as the Naval Architecture tool was selected to model the catamaran hull form design using the MAXSURF modeler and the MAXSURF stability was employed to carry out the stability analysis. The stability analysis was conducted using the intact stability criteria of IMO. The stability assessment was performed to verify whether the vessel's stability complies with international standards. A numerical method (Simpson's rules) was employed in evaluating the area under the GZ curves within the range: 0º - 30º; 0º - 40º; 30º - 40º. The maximum heeling moment was calculated as 954.48 tons-m for load case 1; 755.36 tons-m for load case 2; 671.58 tons-m for load case 3 and the range of stability for all three load cases was justified well. It was concluded that the Catamaran at full load (Load case 1) is more stable with a maximum heeling moment of 954.48 tons-m as compared to Load cases 2 and 3

Keywords: Catamaran; Stability; Draught; Vessel; Safety; MAXSURF

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1. Introduction

The concept of stability can be deemed as one of the most important areas of focus in ship design and operation, not only to ensure the safety of the ship, cargo, crew, and passengers but also to enable proper conditions for all the processes on the vessel to be completed (Soumya, 2021). Stability is determined by the force of buoyancy provided by the underwater parts of a vessel, coupled with the combined weight of its hull, equipment, fuel, stores, and load. The prevailing weather conditions and sea state can also adversely affect these forces. Understanding the factors that influence stability will assist skippers in making the right decisions and taking the right actions to keep their vessels safe. Understanding a surface ship's stability can be divided into two parts. First, Intact Stability. This field of study deals with the stability of a surface ship when the intactness of its hull is maintained, and no compartment or watertight tank is damaged or freely flooded by seawater. The study of a surface ship's damaged stability includes identifying compartments or tanks subjected to damage and flooding by seawater, followed by a prediction of resulting trim and draft conditions (Nitonye et al., 2021).

In the past, most waterborne craft were made up of monohulls because they provided a simple solution to the problem of transportation at a minimum cost but provided low stowage space for payload with minimum speed, poor stability, and greater resistance. With the stabilizing hull to the main hull to maximize speed, providing as much stowage space for payloads, minimize resistance, and improve overall stability, the catamaran vessel became more stable than other single-hull vessels (Nitonye et al., 2013). A catamaran is a surface vessel that offers many advantages related to space, surface, and stability in maritime exploitation. Its rate of stability satisfies sailing requirements regarding space and stability as well as other functional needs of the users (Liang et al., 2019). Tamunodukobipi and Nitonye, (2019)

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considered the performance characterization of a 72 m-long catamaran using hydrodynamic relations and numerical methods

Putranto et al. (2018) approached the intact stability of a catamaran by the length of metacenter to gravity (MG) and resistance analysis by the Van Oortmerssen Method. He concluded that the positions of the metacenter that indicate the stability of the ship is still located above the gravity point either the full load condition or the empty condition and the maximum GZ at full load condition is about 1.2 m and one at empty load condition is about 0.4 m. Dubrovsky, (2010) analyzed the influence of a series of shape parameter changes on a Catamaran's navigability. However, there is no relation between the shape of the Catamaran and the design of the upper and lower body. The form underwater can be changed arbitrarily, and it will not affect the length and width of the entire deck. On the other side, the problem of the monohull ship's stability is solved by the adequate loading of additional weights into the vessel (ballast) (Kos et al., 2010; McVicar et al., 2018). There are two basic design types of catamarans: the pontoon and the SWATH (Small Water-plane Area Twin Hull).

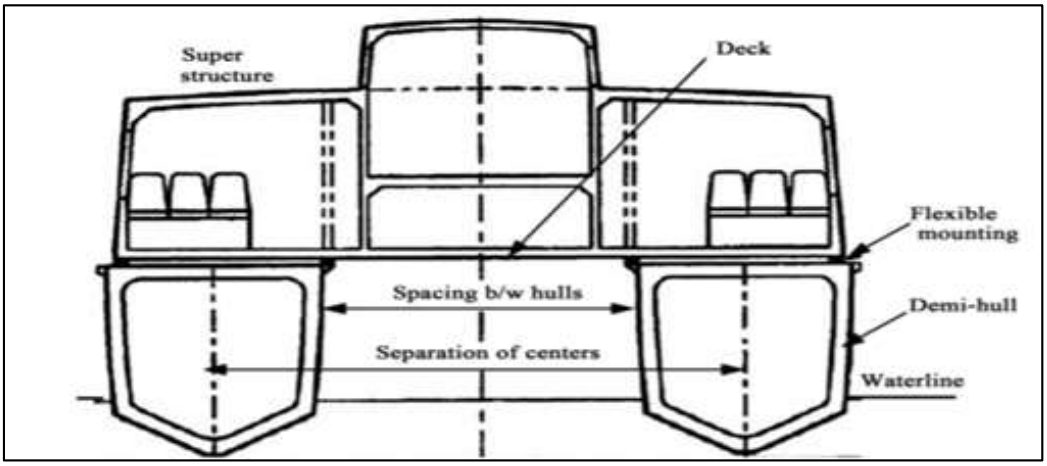

Figure 1 Schematics of a Catamaran showing twin demi-hulls

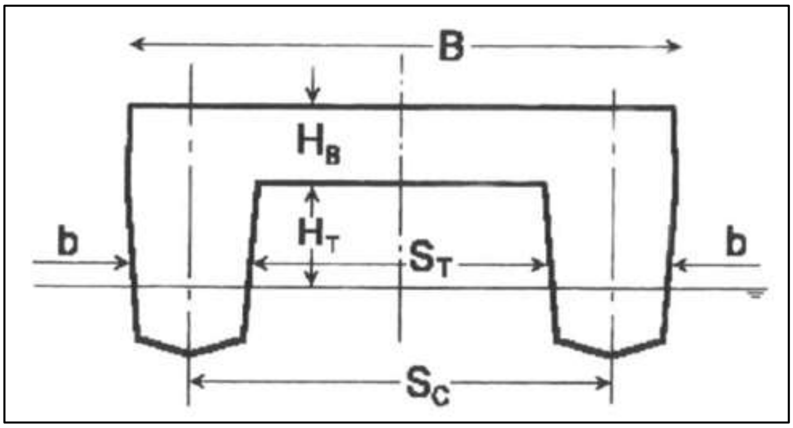

Figure 2 Basic Catamaran Dimensions

In Figure 2 the basic dimensions of the catamaran are presented. B means overall beam of the craft, b means beam of each hull, S_C means hull separation, S_T means width between the inside hull surfaces (the tunnel), H_T means height of the underside of the bridging structure and H_B means depth of the bridging structure. The hulls provide buoyancy and housing for the propulsion machinery, while the bridging structure provides the transverse strength of the craft (Tamunodukobipi & Nitonye, 2019). Stability has been a primary focus of the maritime industry, and the surface ship's stability can be divided into two parts. Intact Stability and Damaged Stability (Nitonye and Adumene 2014; Dracos, 2019; Liang et al., 2019; Nitonye et al., 2023)

1.1. Intact Stability of Surface Ships

The fundamental concept behind the understanding of the intact stability of a floating body is that of Equilibrium. Three types of equilibrium conditions can occur, that is Stable, unstable, and neutral equilibrium (Derrett & Barrass 1999).. The easiest and handiest tool for analyzing a surface ship's stability is graphs or curves. A ship designer or an officer on board should be able to know the stability characteristics of a ship just by looking at the curves. Since the stability of a vessel is to the value of its metacentric height (GM) which is directly related to the righting lever (GZ) and angle of heels, The graph below is plotted assuming that the ship is in static condition.

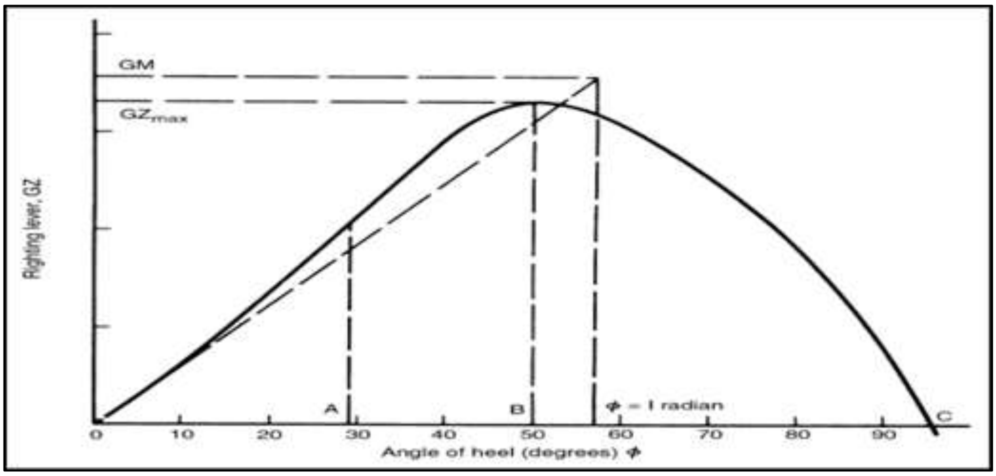

Figure 3 Static Stability Curve / GZ Curve of a Surface Ship

In the graph, the Maximum righting lever (GZ_{MAX}) is proportional to the largest static heeling moment. This is required to bring the ship back to its upright position. The value of maximum GZ and the angle at which it occurs are important. In other words, the maximum righting lever multiplied by the displacement gives us the value of the maximum heeling moment that the ship can sustain without capsizing. The point where the GZ curve meets the horizontal axis is called the point of vanishing stability since the righting lever becomes zero at this point. So, any heel beyond this angle would result in negative stability. The distance between the origin and the point of vanishing stability is called the range of stability of a ship. The steeper initial slope of the GZ curve would mean that the ship has more initial stability. However, larger initial stability does not imply larger values maximum righting lever, and range of stability.

The angle of Loll: The initial metacentric height of the ship can become negative, so the ship is not stable in its upright condition, leading to a heeling moment.

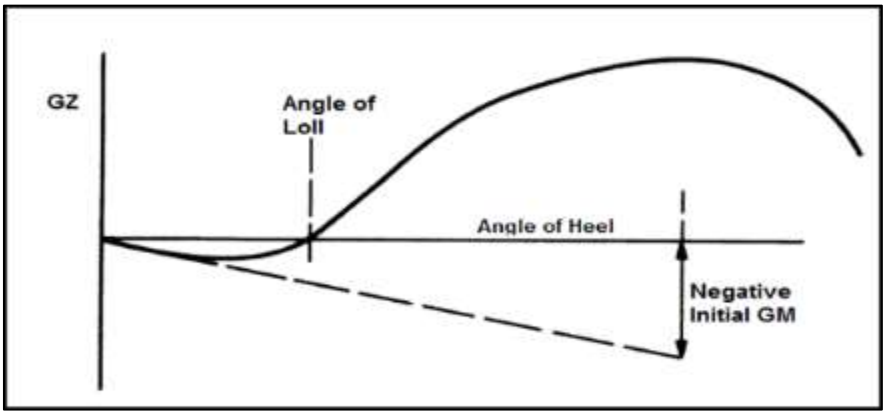

Figure 4 GZ curve for a ship having an angle of loll

1.2. Longitudinal Stability

In all that we have discussed till now, we have dealt with only the heeling of a ship. In other words, we have been discussing only the transverse stability of a vessel. Remember that a ship's stability analysis isn't limited to just the transverse direction. Longitudinal shifts in onboard weights, or any longitudinal trimming moment (a moment that would cause the ship to trim), are also important factors discussed under the longitudinal stability of a vessel. Some characteristic parameters calculated for a floating ship, which can either directly be used to comment on the nature of stability of the vessel or be used to evaluate other stability parameters, are called ship hydrostatics. For a designer to develop a hull form, or a ship's captain to understand the stability parameters, both need to understand the meaning and practical significance of each hydrostatic parameter of a surface ship. The hydrostatics of a surface ship include the Vertical, Longitudinal, and Transverse Center of Gravity, Vertical, Longitudinal, and Transverse Center of Buoyancy, Mass Displacement (Δ), Volume Displacement (∇), and Longitudinal and Transverse Centre of Floatation. Others are Metacenter, Metacentric Height, Metacentric Radius, Moment to Change Trim 1 cm (MCT), and Tons per cm Immersion (TPC). Before we move on, another important technique used to analyze the ship's hydrostatics and stability parameters is that of stations, a ship's hull is longitudinally divided into stations, which are nothing but specified positions along the length of the vessel about the aft perpendicular which is numbered as zero station.

2. Materials and Methods

The International Maritime Organization (IMO) has formulated rules (SOLAS) to ensure adequate stability for ships during operation. The Rules for intact stability are given in Annexure-1. The main requirements of properties of the GZ curve are as follows (heeling moment due to external forces is considered.

- The initial metacentric height GM_O should not be less than 0.15 m.
- The righting lever GZ should be at least 0.20 m at an angle of heel equal to or greater than 30^O.
- The maximum righting arm should occur at an angle of the heel preferably exceeding 30^O but not less than 25^O
- The area under the righting lever curve (GZ curve) should not be less than 0.055 meter-radian up to $\theta = 30^O$ angle of the heel.
- The area under the righting lever curve should not be less than 0.09-meter radian up to $\theta = 40^O$ or the angle of flooding θ_i if this angle is less than 40^O .
- The area under the righting lever curve between the angles of the heel of 30^O and 40^O or between 30^O and θ_i , if this angle is less than 40^O, should not be less than 0.03 meter radius.

2.1. Vessel Parameters

Table 1 Parameters of the vessel

Length overall	42.2 m
Beam overall	11.6 m
Depth at sides	3.8 m
Draught max	1.6 m

2.2. Catamaran Transverse Stability

The calculation of catamaran buoyancy is the same as for a conventional monohull craft, considering the two separate hulls but the calculation of the transverse stability of a catamaran is a little different due to the hull separation. Catamaran Stability for Small Disturbance; for small heel angles, the buoyancy force may be considered to act vertically upwards through a fixed point called the initial metacenter (M). This is shown in Figure 5, in which the ship is inclined to a small angle (θ degrees).

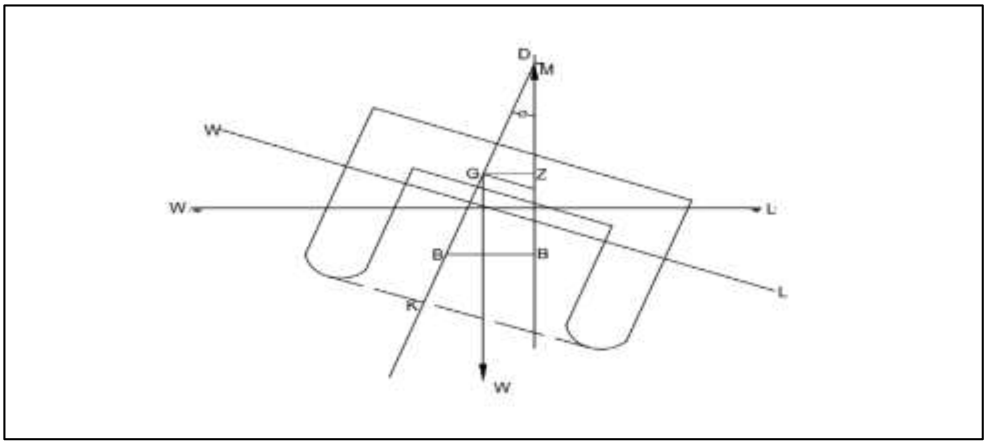

Figure 5 Stability at small disturbance

With the location of G and M known, the righting arm for small angles of the heel can be calculated readily, with sufficient accuracy for all practical purposes, by the formula.

$$GZ = GM \times \sin\theta^{o} \quad \text{………………(1)}$$

The distance GM is therefore important as an index of transverse stability at small angles of the heel, and it is called the transverse metacentric height.

The initial transverse metacentric height above the vertical CG, for a catamaran can be calculated as follows:

$$GM = BM + \left(z_c - z_g\right)$$

$$GM = \frac{2\gamma\left(I_x^d + k_d^2 S_d\right)}{D} + \left(z_c - z_g\right) \quad \text{…………(2)}$$

Where $BM =$ Initial transverse metacentric radius (m); $I_x^d =$ Moment of inertia of demi hull waterline area to the x-axis of demi hull (m^4); $\gamma =$ Density of water (t/m^3); $k_d =$ Distance between catamaran longitudinal centerline and demi hull centerline (m); $S_d =$ Area of demi hull design waterline plane (m^2); $z_c, z_g =$ Height of catamaran center of buoyancy and C.G. from baseline (m); $D =$ Displacement of catamaran (t).

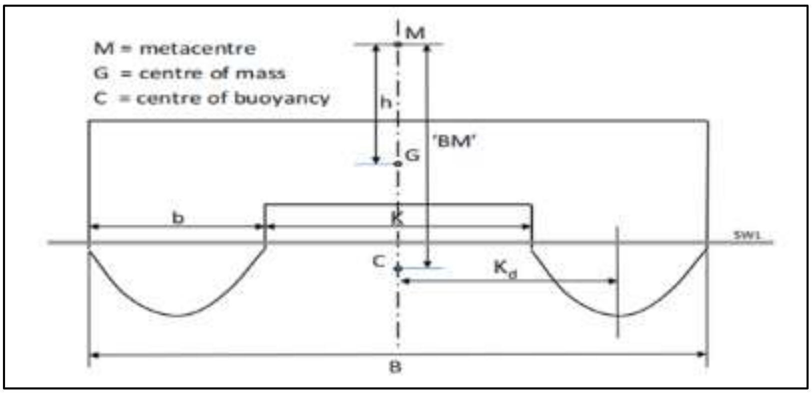

Figure 6 Geometry cross-section diagram

I_x^d can be obtained using the lines of the demi hulls as follows.

$$I_x^d = \frac{2}{3}\int_{-L/2}^{+L/2} y^3 dx = \frac{2}{3}\Delta L \sum y^3,$$

Where $y =$ Coordinate value of demi hull waterline, from the longitudinal central plane and $\Delta L =$ Space between stations.

If hull lines are lacking at the preliminary design stage, one can use the following formula for an approximate estimation:

$$I_x^d = \frac{D}{2y} \times \frac{a^2 b^2}{11.4\delta T} \quad \text{.................(3)}$$

Where: *a* = Demi hull waterline area coefficient C_w;, *b* = Demi hull beam at midships or central parallel (m); T = Demi hull draft at keel (m) and δ =Demi hull block coefficient C_b.

The height of the center of buoyancy z_c can also be obtained empirically where there are no hull lines at the initial design stage by referring to the expected waterline area coefficient and the demi hull expected block coefficient as follows:

$$z_c = \frac{T}{1+\delta / a} \quad \text{................(4)}$$

Thus, the transverse metacentric height can be estimated. When comparing the monohull, the GM will be four times greater. The moment of statical stability at a small angle of heel is expressed as:

Moment of statical stability = $W \times GZ$

$\therefore$ Moment of statical stability = $W \times GM \times \sin\theta^o$ ....(5)

2.3. Catamaran Stability for Larger Disturbances

At a large angle of the heel, the force of buoyancy can no longer be considered to act vertically upwards through the initial metacenter (M). This is shown in Figure 3.3, where the ship is heeled to an angle of more than 15 degrees. The center of buoyancy has moved further out to the low side, and the vertical through B_1 no longer passes through (M), the initial metacenter. The righting lever (GZ) is once again the perpendicular distance between the vertical through G and the vertical through B_1, and the moment of statical stability is equal to W × GZ.

But GZ is no longer equal to $GM \sin\theta^o$. Up to the angle at which the deck edge is immersed, it may be found by using a formula known as the ***Wall-sided formula.*** i.e.

$$GZ = (GM + \frac{1}{2} BM \tan^2\theta)\sin\theta \quad \text{..............(6)}$$

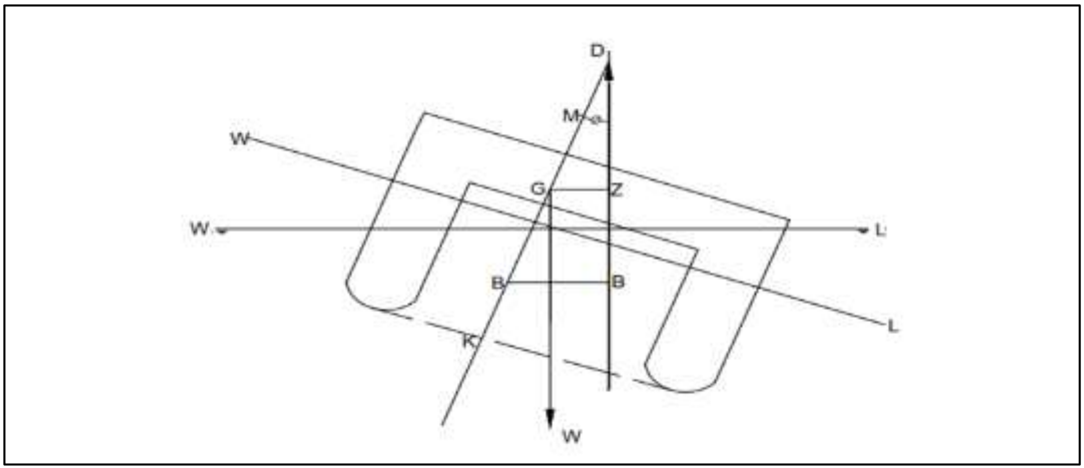

Figure 7 Effect of large Angle of Heel on a Catamaran

The derivation of the formula is as follows:

Refer to the ship shown in Figure 8. When inclined the wedge WOW$_1$ is transferred to LOL$_1$ such that its Centre of gravity shifts from B to B$_1$. The horizontal components of these shifts are hh$_1$ and BB$_2$ respectively, the vertical components being (gh + g$_1$h$_1$) and B$_1$B$_2$ respectively. Let BB$_2$ be 'a' unit and let B$_1$B$_2$ be 'b' units.

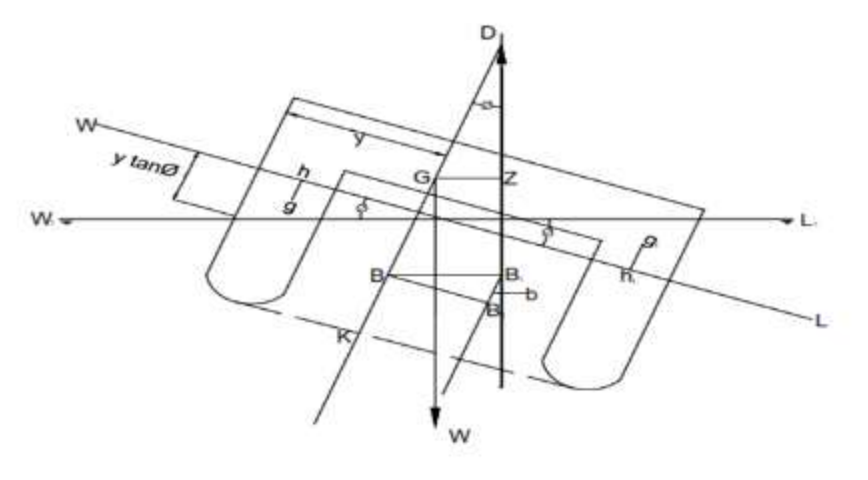

Figure 8 Stability at large angles

Now consider the wedge LOL$_1$

$$Area = \frac{1}{2} y^2 \tan\theta$$

Consider an elementary strip longitudinally of length dx

$$Volume = (\frac{1}{2} y^2 \tan\theta) dx$$

The horizontal shift from the wedge (hh1), is $\frac{2}{3} \times 2y$ or $\frac{4}{3} \times y$

$\therefore$ Moment of shifting this wedge $= \frac{4}{3} y \times \frac{1}{2} y^2 \tan \theta dx = \frac{2}{3} y^3 \tan \theta dx$

The sum of the moment of all such wedges $= \int_0^L \frac{2}{3} y^3 \tan \theta dx = \tan \theta \int_0^L \frac{2}{3} y^3 dx$

But the second moment of the water-plane area about the Centerline

$$I = \int_0^L \tfrac{2}{3} y^3 dx$$

$\therefore$ The sum of the moment of all such wedges $= I \times \tan \theta$

$$BB_2 = \frac{v \times hh_1}{V}$$

$$V \times BB_2 = v \times hh_1$$

But the sum of the moments of the wedges $= v \times hh_1$

$$\therefore V \times BB_2 = I \times \tan \theta$$

$$BB_2 = \frac{I}{V} \times \tan \theta$$

$$BB_2 = BM \times \tan \theta$$

The vertical shift of the wedge $= gh + g_1 h_1 = 2gh$

$\therefore$ The vertical moment of the shift $= v \times 2gh = 2vgh$

By simple substitution, the GZ is obtained to be

$$GZ = \sin \theta (GM + \frac{1}{2} BM \tan^2 \theta)$$

This is the Wall-sided formula.

Note: This formula may be used to obtain the GZ at any angle of the heel so long as the ship's side at WW_1 is parallel to LL_1, but for small angles of the heel (θ up to 5°) the term $\frac{1}{2} BM \tan^2 \theta$ may be omitted.

The moment of statical stability at a large angle of the heel may also be calculated using a formula known as Attwood's formula: i.e.

Moment of statical stability $= W\left(\frac{v \times hh_1}{V} - BG \sin \theta\right)$ …………………… (7)

The derivation of the formula is as follows:

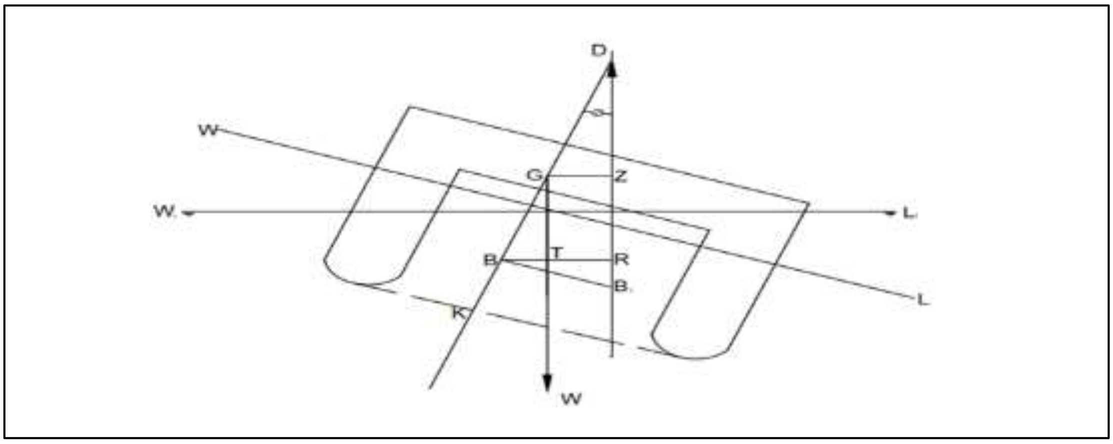

Figure 9 Stability at a large angle

$$\text{Moment of statical stability } = W \times GZ = W(BR - BT)$$

Let v = the volume of the immersed or emerged wedge, hh_1 = the horizontal component of the shift of the Centre of gravity of the wedge, V = the underwater volume of the ship, and BR = the horizontal component of the shift of the Centre of buoyancy

$$BT = BG \sin\theta$$

also

$$BR = \frac{v \times hh_1}{V}$$

$$\therefore \text{ Moment of statical stability } = W\left(\frac{v \times hh_1}{V} - BG\sin\theta\right)$$

Once the preceding calculations have been made, it is necessary to construct the transverse stability curves for the vessel and verify that the requirements specified by the IMO can be met.

2.4. Catamaran Longitudinal Stability

The initial longitudinal metacentric height H (GM_L) can be written as;

$$GM_L = BM_L + (z_c - z_g) \quad \text{………………(8)}$$

BM_L may be estimated as follows for a typical catamaran:

$$BM_L = \frac{a^2}{14\delta} \times \frac{L^2}{T} \quad \text{……………………..(9)}$$

The characteristic of a catamaran has a higher transverse stability than that of a conventional monohull due to demi hull separation but a smaller longitudinal stability than that of conventional monohulls due to demi hull fineness of form.

2.5. Statical Stability Curves

The curve of statical stability for a ship in any loading condition is obtained by plotting the righting levers against the heel angle as shown in Figures 11 and 12.

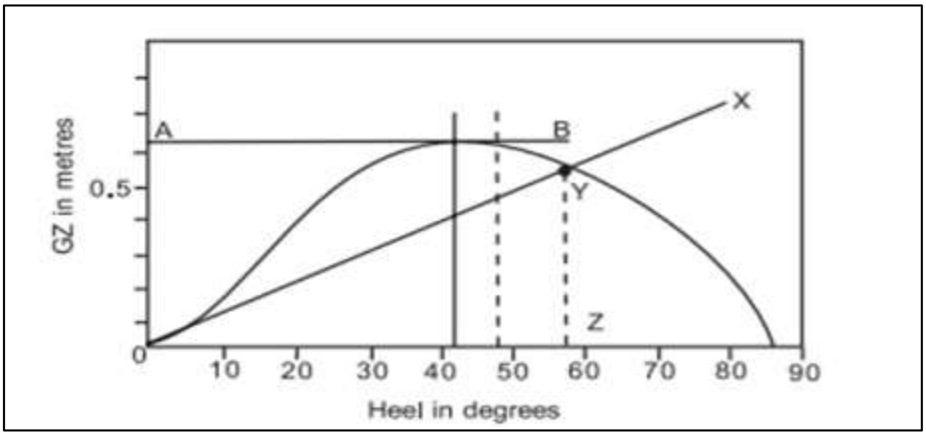

Figure 10 Curve for a ship with positive initial metacentric height

From this type of graph, a considerable amount of stability information may be found by inspection:

- **The range of stability:** This is the range over which the ship has positive righting levers.
- **The angle of vanishing stability:** This is the angle of the heel at which the righting lever returns to zero or is the angle of the heel at which the sign of the righting levers changes from positive to negative.
- **The maximum GZ** is obtained by drawing a tangent to the highest point in the curve. In Figure 11, AB is the tangent, and this indicates a maximum GZ.
- **The initial metacentric height** (GM) is found by drawing a tangent to the curve through the origin (OX in Figure 11) and erecting a perpendicular through an angle of heel of 57.3 degrees. Let the two lines intersect at Y. Then the height of the intersection above the base (YZ), when measured on the GZ scale, will give the initial metacentric height.

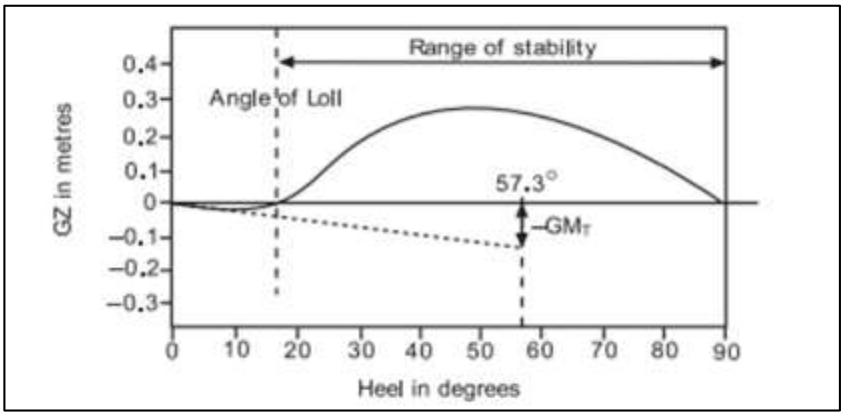

Figure 11 Curve for a ship with negative initial metacentric height

2.6. Dynamic Stability

This is the stability characteristic of the vessel when moving (particularly rolling) and is the energy necessary to incline a vessel to a certain angle of heel and thereby counteract the moment of statical stability.

The dynamic stability may be determined by measuring the area under the righting lever curve (GZ curve) up to a certain angle of heel. The larger the area, the better is the dynamic stability.

The area under the curve can be determined using Simpson's rules thus:

2.6.1. Simpson's First Rule

This rule assumes that the curve is a parabola of the second order.

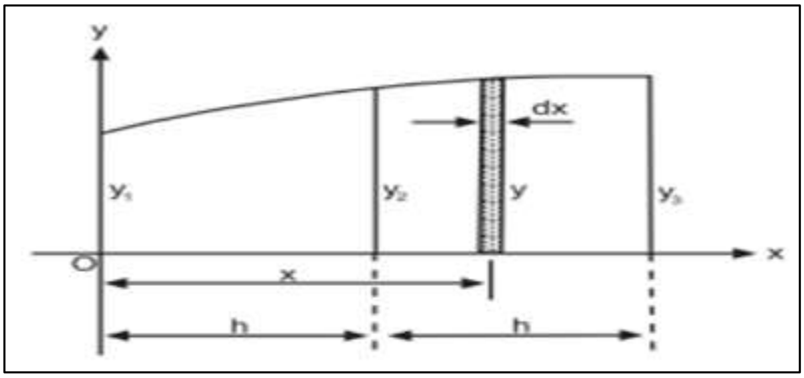

Figure 12 Simpson's 1/3 rule

$$\therefore \text{ Area of figure } = \frac{h}{3}(y_1 + 4y_2 + y_3) \quad \text{…………….(10)}$$

This is Simpson's First Rule. A coefficient of $\frac{1}{3}$ with multipliers of 1, 4, 1 etc.

2.6.2. Simpson's Second Rule

This rule assumes that the equation of the curve is of the third order.

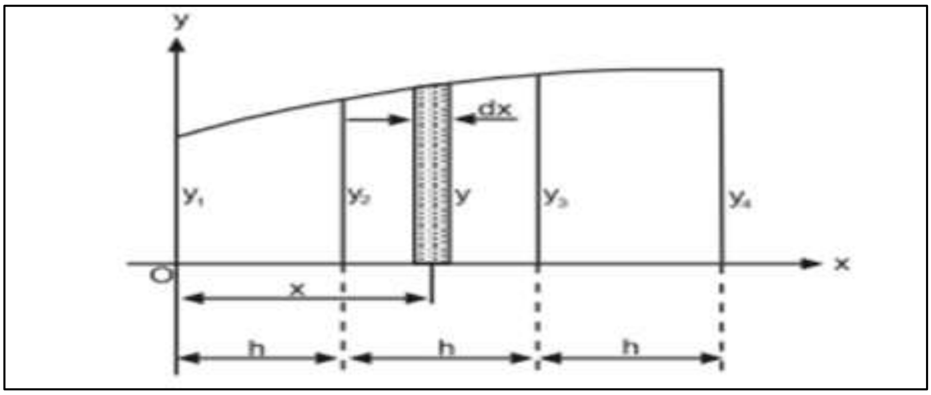

Figure 13 Simpson's 3/8 rule

$$\text{Area of figure } = \frac{3}{8}h(y_1 + 3y_2 + 3y_3 + y_4) \quad \text{……………..(11)}$$

This is the Simpson's second rule. A coefficient of $\frac{3}{8}$ with multipliers 1,3,3,1 etc

2.6.3. Simpson's Third Rule

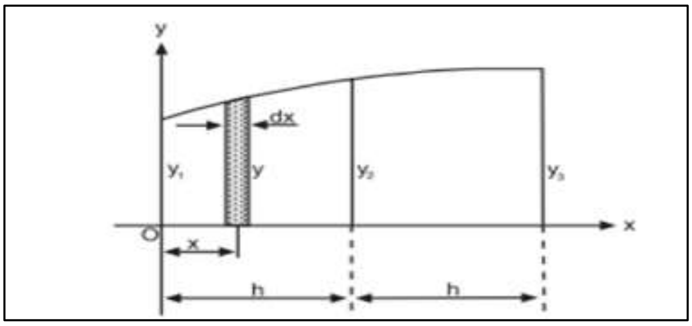

Figure 14 Simpson's third rule

$$\text{Area} = \frac{h}{12}(5y_1 + 8y_2 - y_3) \qquad \text{………………………..} \quad (12)$$

This is the Five/eight (or five/eight minus one) rule and is used to find the area between two consecutive ordinates when three consecutive ordinates are known. It has a coefficient of $\frac{1}{12}$ with multipliers of 5, 8, -1, etc

2.7. Ship Hull Form Line Plan

The ship hull form is the watertight enclosure of the vessel, which protects the cargo hold, machinery, and accommodation spaces of the ship form from weather, flooding, and structural damage (Lamb, T., 2003). Maxsurf modeler was used to produce the ship hull plan.

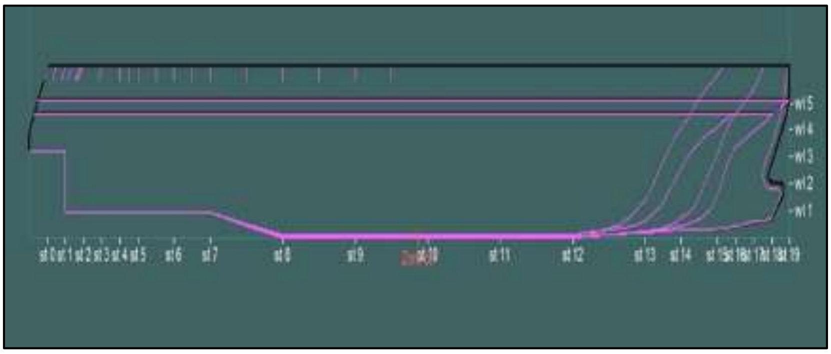

Figure 15 Profile view

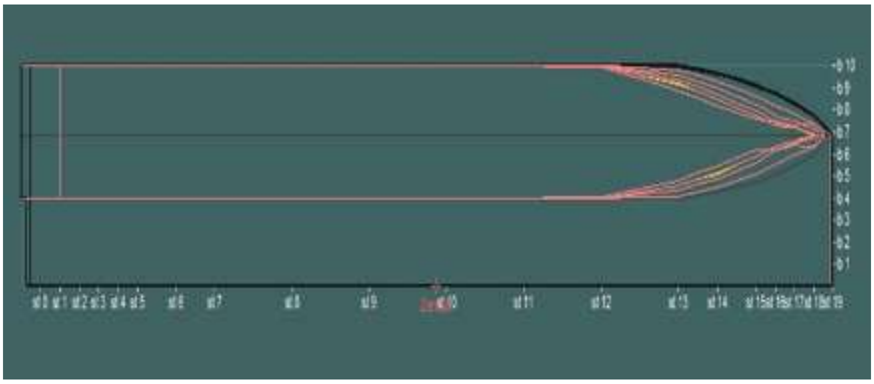

Figure 16 Plane view

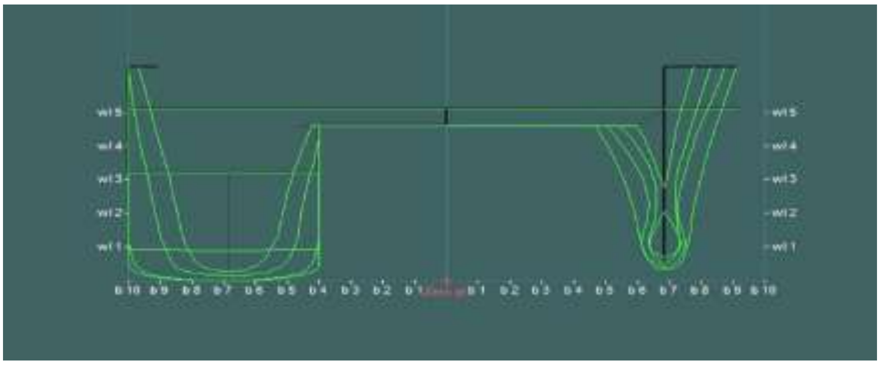

Figure 17 Body plan view

2.8. Three-Dimensional Ship Hull Form

The lines plan provides for the foundation of developing not only the three-dimensional hull model as shown in Figure 4.4, but also the development of the frame-wise structural drawings, general arrangement, and loft drawings at the shipyard (Schneekluth & Bertram 1998).

2.8.1. Tanks and Compartments

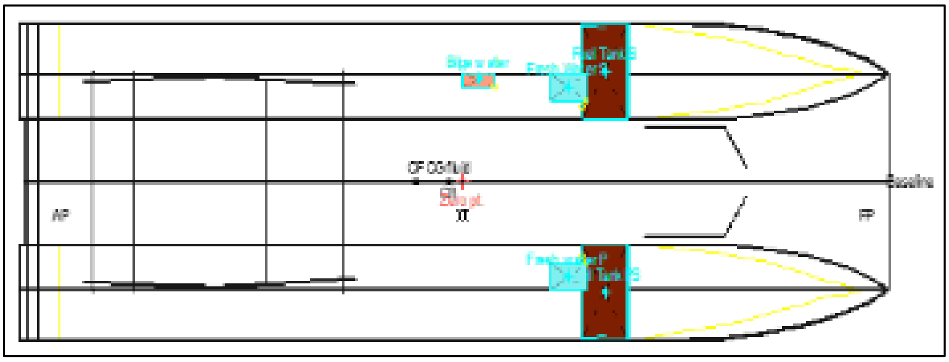

Figure 18 Tanks (plane view)

3. Results and Discussion

The result obtained from the stability curve for load-case 3 demonstrates that the maximum righting lever (GZmax) was 3.198m when the vessel heeled to an angle of 15.9^0. This angle implies the largest static heeling moment (671.58 tons-m) that is required to bring the ship back to its upright position. Beyond, the angle of 15.9^0 the righting lever or stability of the catamaran drastically decreases to a negative GZ at an angle of 75^0. The point of vanishing stability occurs at two points 70^0 and 142^0–degrees, at these points righting lever becomes zero as shown in Figures 19 to 21. So, any heel beyond these angles would result in a condition of negative stability. From the stability curve neglecting the small area that resulted from the first point of vanishing stability, it can be said that the Catamaran has a range of stability beyond 140^0 when considering lightship alone. Figure 22 shows the hydrostatic parameters of the catamaran

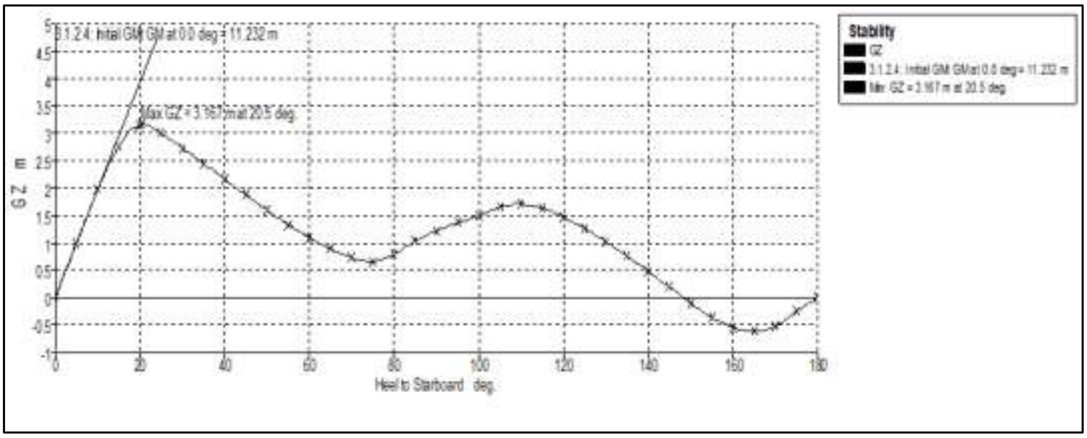

Figure 19 Statical stability curve for load case 1

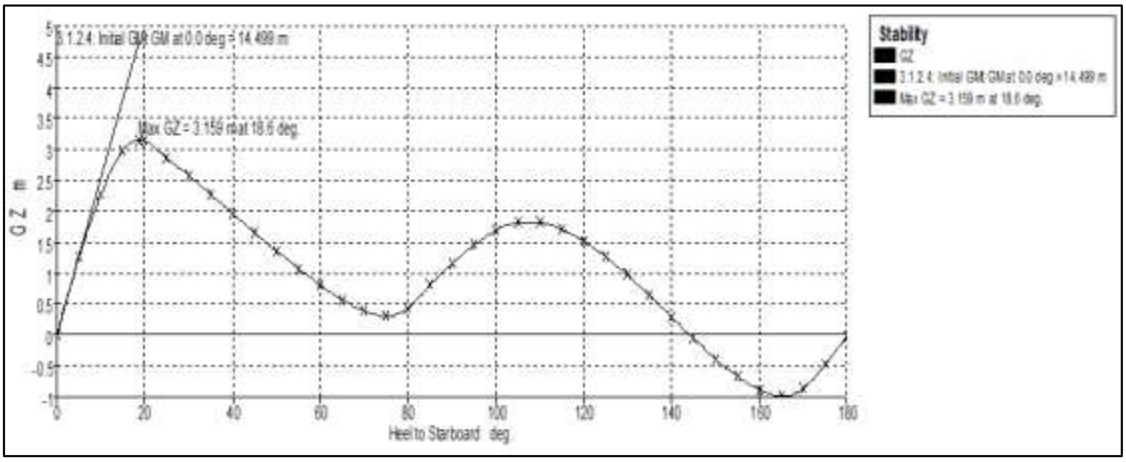

Figure 20 Statical stability curve for load case 2

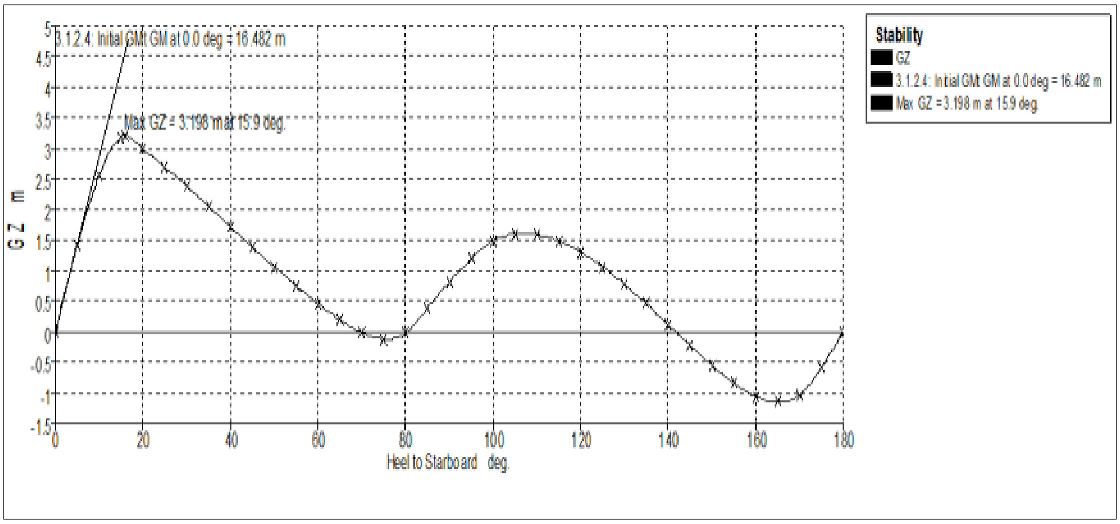

Figure 21 Statical stability curve for load case 3

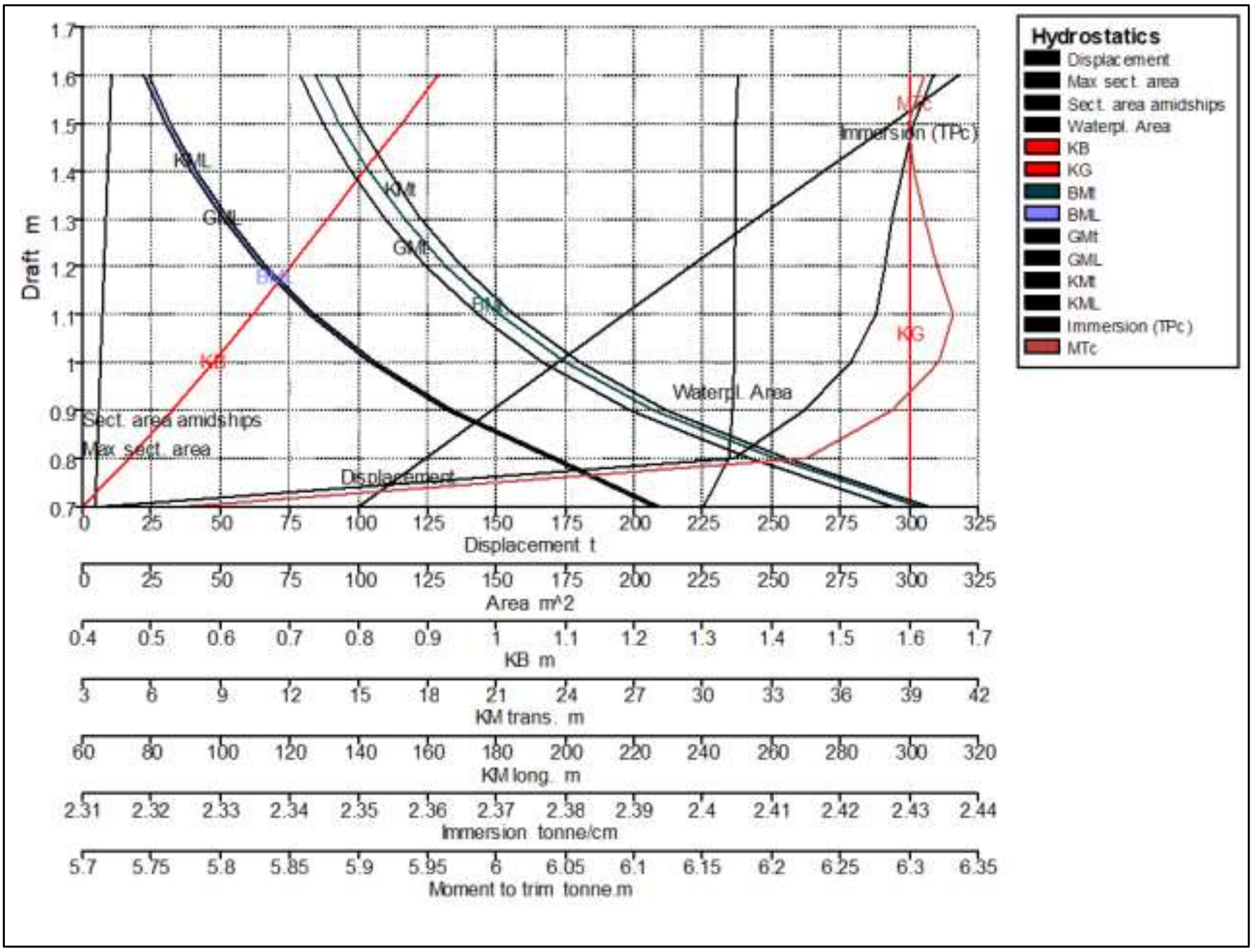

Figure 22 Hydrostatic curves of the Catamaran

4. Conclusion

The study of intact stability of a surface ship helps to produce better allocation and arrangement plans for machinery, cargo hold, equipment (crane), and stowage, and ensure sufficient stability for the vessel satisfying the IMO-SOLAS Intact Stability Criteria. The distinctive feature of a catamaran is its higher transverse stability than the conventional mono-hull due to demi-hull separation. The same data for the vessel displacement characteristics, together with the mass and center of gravity for the vessel were used to assess static stability and to calculate the righting moment available from the upward buoyancy force compared with the overturning moment from the vessel mass operating at its vertical Centre of gravity (VCG) and any other disturbing forces. During the stability analysis, it was observed that the maximum righting lever (GZ max) multiplied by the displacements of the vessel yields the maximum heeling moment the ship can withstand without capsizing. These are used when the vessel is operating in a loading condition that it has not operated on before; The GZ curve can be obtained easily, and the vessel's stability determined. It can be said that the Catamaran at full load (Load case 1) is more stable with a maximum heeling moment of 954.48 tons-m as compared to Load cases 2 and 3 having a maximum heeling moment of 755.364 tons-m and 671.58 tons-m Respectively.

It can be concluded that the stability of a surface ship can be measured with two parameters: the metacentric height (GM); and the range (area) of stability. From the result analysis, the values of these parameters comply with the IMO minimum criteria for intact stability of a surface ship with an exception for one design criterion: the angle of maximum GZ. Finally, the subject of ship design and stability needs continuous and extensive research aimed at enhancing safety.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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