Intact Stability Analysis of a Catamaran Vessel

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Abstract

This study examines the intact stability analysis of a passenger catamaran ship under three distinct load scenarios: a lightship with full tanks, a lightship with no passengers, crew, or empty tanks, and a fully loaded ship to maximum free-board draught. The catamaran hull form design was modeled using the maxsurf program as the Naval Architecture tool, and the stability study was conducted using the maxsurf stability. According to the intact stability criteria in IMO A.749 (18) Ch. 3.1.2.1-4, the stability analysis was carried out. The purpose of the stability assessment was to confirm that the vessel's stability meets international requirements. The area beneath the GZ curves in the following ranges was evaluated using a numerical technique (Simpson's rules): 0º to 30º; 0º to 40º; and 30º to 40º. The range of stability for all three loadcases was adequately justified, and the maximum heeling moment was determined to be 954.48 tonnes-m for loadcase 1, 755.36 tonnes-m for loadcase 2, and 671.58 tonnes-m for loadcase 3.With a maximum heeling moment of 954.48 tonnes-m, the Catamaran at full load (Loadcase 1) was shown to be more stable than Loadcases 2 and 3.

Keywords: *Catamaran, Stability Analysis, vessels, load case, meta-centric.*

Introduction

Stability is a crucial aspect of ship design and operation, ensuring the safety of the ship, its cargo, crew, and passengers. (Dracos, 2019) It is determined by the total weight of a vessel's hull, gear, fuel, stores, and load, as well as the buoyant force produced by its submerged components. Stability can be affected by sea-state and current weather. (Liang, 2019) There are two components to understanding the stability of a surface ship: Intact Stability, which examines the stability while the hull remains intact, and Damaged Stability, which investigates the stability of compartments or tanks that have been damaged and flooded by seawater. Catamarans, multihulled vessels with two equal-sized parallel demi-hulls, offer exceptional sea-keeping ability and are a better option for passenger ships than traditional monohulls due to their speed, size, and stability.

Catamarans provide numerous advantages in terms of space, surface, and stability in marine exploitation compared to traditional passenger vessels. (Mcvicar, 2018) Their high stability rate satisfies users' other functional needs, including sailing requirements for stability and space. Research has shown that the frictional resistance (RF) of catamarans is marginally higher than that of monohulls, with wave-making resistance dominating at low speeds. (Soumya, 2021) The Van Oortmerssen Method and dynamic system sensitivity approach have also been used to analyze the stability of catamarans. Finally, shape parameter adjustments can affect a catamaran's navigation ability, but there is no connection between the shape and the upper and lower body designs (Tamunodukobipi & Nitonye 2019).

Material and Method
Catamaran Data Specification

Table 1. **Catamaran principal dimensions**

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

Table 2 **payload and capacities**

Fuel	$14.0m^3$
Fresh water	$2.5m^3$
Sewage	$2.5m^3$
Bilge	$0.5m^3$
Total passenger	445
Crew	5
Luggage	5kg per passenger

2.1.2 VESSEL DESCRIPTION

Table 3: **frame of reference**

Aft Perpendicular	-19.537 m
Midships	0 m
Fwd Perpendicular	19.537 m
Length Between Perpendiculars	39.074 m
Baseline	0 m
DatumWL	1.6 m

Table 4: **Fluid density in use**

Fluid type Nb	fluid name	relativedensity
1	1.025	sea water
3	1.000	fresh water
4	0.840	diesel

Methodology

This study investigates the stability of a catamaran using numerical methods and KRYLOV techniques. The GZ curve, also known as the Static Stability Curve, is used to demonstrate the ship's seaworthiness and compliance with SOLAS regulations. The vessel structure is designed based on mission requirements and statistics from previous vessels. Numerical techniques are used to support the findings, and stability curves and static righting moments are plotted to determine if the crafts meet IMO intact stability requirements. The SOLAS regulations, created by the International Maritime Organization (IMO), include a minimum initial metacentric height of 0.15 meters, a righting lever GZ of 0.20 meters at an angle of heel equal to or greater than, a maximum righting arm, an area under the righting lever curve of at least 0.055 meters radian up to the angle of heel, and an area under the righting lever curve of at least 0.09 meters radian up to or the angle of flooding.

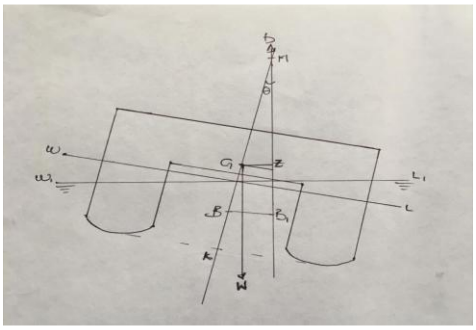

Figure .2: Stability at small disturbance

The righting arm for small angles of heel can be calculated with accuracy using the formula

$$GZ = GM \times \sin \theta^o$$

(1)

where G and M are known. This distance, called the transverse meta-centric height, is crucial for transverse stability at small angles of heel.

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

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

Where

$BM =$ Initial transverse meta-centric radius (m);

$I_x^d =$ Moment of inertia of demihull waterline area with respect to x-axis of demihull (m^4);

$\gamma =$ Density of water (t/m^3);

$k_d =$ Distance between catamaran longitudinal centerline and demihll centerline (m);

$S_d =$ Area of demihull 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).

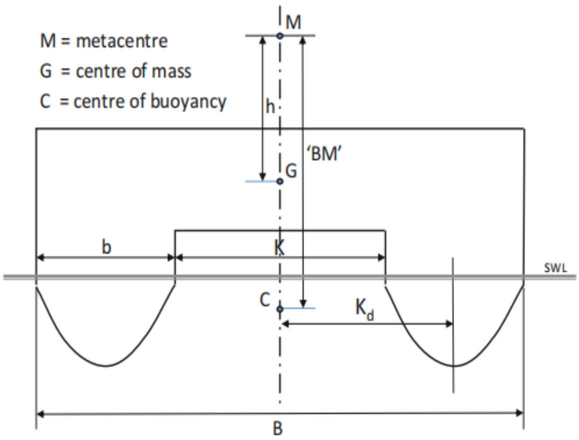

Figure 3. Geometry cross-section diagram

I_x^d Can be obtained using the lines of the demi-hulls as follows;

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

Where

$y =$ Coordinate value of demi-hull waterline, from longitudinal central plane;

$\Delta L =$ Spacing between stations.

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

$$I_x^d = \frac{D}{2y} \times \frac{a^2 b^2}{11.4\delta T} \qquad (4)$$

Where

a = Demihull waterline area coefficient C_w;

b = Demihull beam at midships or central parallel (m);

T = Demihull draft at keel (m);

δ =Demihull 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 demihull expected block coefficient as follows:

$$z_c = \frac{T}{1+\delta/a} \qquad (5)$$

Thus the transverse metacentric height can be estimated. In comparison with a monohull, the GM will be up to four times as great due to demihull separation.

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 = $W \times GM \times \sin\theta^o$ (6)

Catamaran Stability for Larger Disturbances

The ship's buoyancy force shifts to the low side, causing a significant angle of heel and a shift in the moment of statical stability.

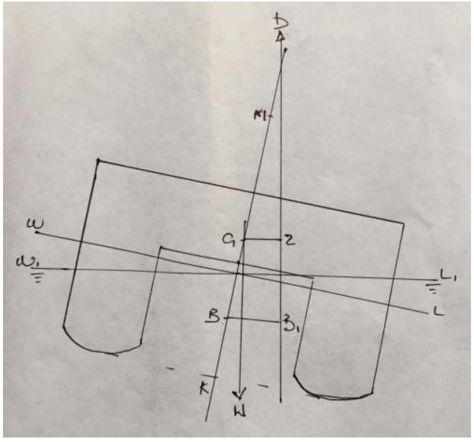

Figure 4. effect of large angle of heel on a catamaran

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.

$$GZ = (GM + \frac{1}{2}BM\tan^2\theta)\sin\theta \qquad (7)$$

The derivation of the formula is as follows:

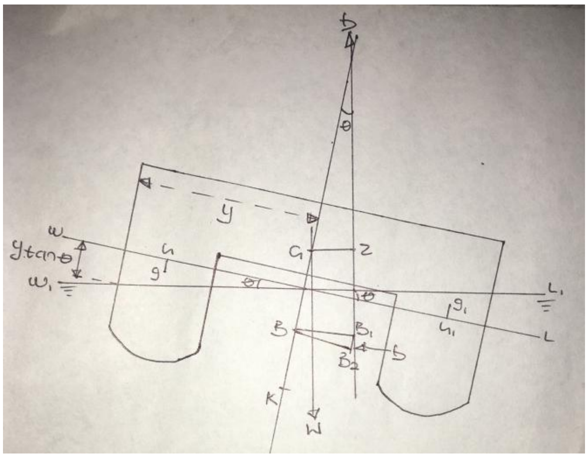

Figure 5: Stability at large angles

Figure 5 illustrates a ship's center of gravity shifting when wedge WOW1 is transferred to LOL1, with horizontal components hh1 and BB2 and vertical components gh + g1h1 and B1B2.

Now consider the wedge LOL_1

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

Consider an elementary strip longitudinally of length dx as in figure 6(b)

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

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 $=\frac{4}{3}y\times\frac{1}{2}y^2\tan\theta dx=\frac{2}{3}y^3\tan\theta dx$

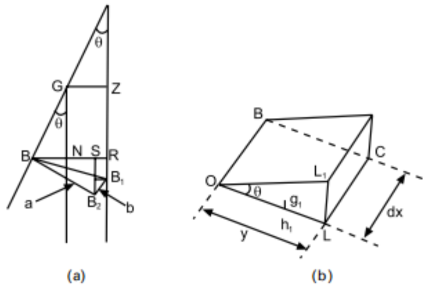

Figure 6

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

But the second moment of the water-plane area about the centre-line

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

$\therefore$ 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 $=v\times hh_1$

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

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

$BB_2=BM\times\tan\theta$ ---------- 'a'

The vertical shift of the wedge $=gh+g_1h_1$

$=2gh$

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

In figure 6(b)

$OL=y$ and $Oh_1=\frac{2}{3}y$

$LL_1=y\tan\theta$

$\therefore g_1h_1=\frac{1}{3}y\tan\theta$

The volume of the wedge $=\frac{1}{2}y^2\tan\theta dx$

The moment of the vertical shift $=\frac{1}{2}y^2\tan\theta dx\times\frac{2}{3}y\tan\theta$

$=\frac{1}{3}y^3\tan^2\theta dx$

The vertical moment of all such wedges $=\int_0^L \tfrac{1}{3}y^3\tan^2\theta dx$

$=\frac{1}{2}I\tan^2\theta$

$\therefore$ The moment of the vertical shift $=\frac{1}{2}I\tan^2\theta$

Also

$$B_1B_2 = \frac{v \times 2gh}{V}$$
$$V \times b = 2vgh$$

but

$$2vgh = \text{The vertical moment of the shift}$$

$$\therefore V \times b = \frac{1}{2} I \tan^2 \theta$$

or

$$b = \frac{I}{V} \times \frac{\tan^2 \theta}{2}$$

$$B_1B_2 = \frac{BM \tan^2 \theta}{2} \text{ ----------------- 'b'}$$

Referring to figure 6(a)

$$GZ = NR$$
$$= BR - BN$$
$$= (BS + SR) - BN$$
$$= a\cos\theta + b\sin\theta - BG\sin\theta$$
$$= BM \tan\theta\cos\theta + \frac{1}{2} BM \tan^2\theta\sin\theta - BG\sin\theta \qquad \text{[from 'a' and 'b']}$$
$$= BM \sin\theta + \frac{1}{2} BM \tan^2\theta\sin\theta - BG\sin\theta$$
$$\text{GZ} = \sin\theta(BM + \frac{1}{2} BM \tan^2\theta - BG)$$
$$GZ = \sin\theta(GM + \frac{1}{2} BM \tan^2\theta) \qquad \text{[for } \theta \text{ up to } 25^o\text{]}$$

This is the Wall-sided formula.
The formula for calculating the GZ at any angle of heel, as long as the ship's side is parallel to LL1, can be omitted for small angles.

$$\text{Moment of statical stability } = W\left(\frac{v \times hh_1}{V} - BG\sin\theta\right) \quad (8)$$

The derivation of the formula is as follows:

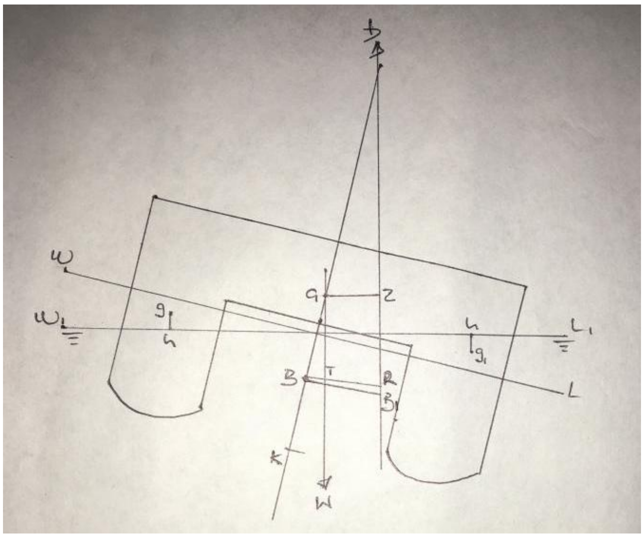

Figure 6: Stability at a large angle

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

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.

Catamaran Longitudinal Stability

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

$$GM_L = BM_L + (z_c - z_g) \quad (9)$$

BM_L may be estimated as follows for a typical catamaran:

$$BM_L = \frac{a^2}{14\delta} \times \frac{L^2}{T} \quad (10)$$

A catamaran's transverse stability is higher than a conventional monohull due to demihull separation, but its longitudinal stability is smaller due to demihull fineness.

Results and Discussion

Results Analysis

Stability Calculation for Fully Loaded Catamaran

Loadcase - Fully loaded ship to maximum free-board draught
Damage Case - Intact
Free to Trim
Specific gravity = 1.025; (Density = 1.025 tonnes/m^3)
Fluid analysis method: Use corrected VCG
Total passengers = 445 ; Crew = 5
A minimum weight of 75 kg shall be assumed for each passenger.

$$\therefore \text{weight/passenger} = \left(\frac{75\text{kg}}{1000}\right)\text{tonnes} = 0.075 \text{ tonnes}$$

$$\text{Total weight of 445 passengers} = 33.375 \text{ tonnes}$$

$$\text{Total weight of Crew} = 0.375 \text{ tonnes}$$

Luggage = 5kg per passengers

$$\text{Total weight of luggage} = \frac{5}{1000} \times (445 + 5) = 2.25 \text{ tonnes}$$

From the loading sheet we arrived at a final displacement of 301.385tonnes, and solid KG of 3.496m.
From equation (1), the righting lever for small disturbance below 15^o angle of heel is:

$$GZ = GM \times \sin\theta^o$$

From equation (6), the righting lever for larger disturbance above 15^o angle of heel is:

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

Equation (1) and (6) are used to calculate for the righting lever, GZ at different angle of heel shown in the table below:

To check the ship's compliance to minimum IMO requirement, Result for stability calculation for loadcase 1 (hydrostatic particulars of the ship) will be used to construct the curve of statical stability (Graph of GZ against heel angle).

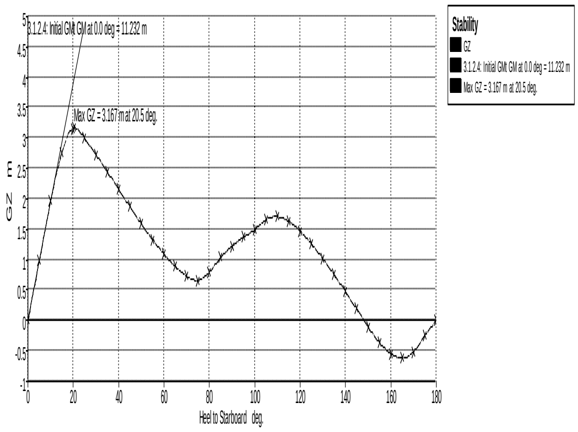

Figure 18: Curve of statical stability for load case 1

Table 5 The area under the righting lever curve (GZ curve) between 0º - 30º

GZ	SM	AREA
O	1	0
1.968	3	5.904
3.162	3	9.486
2.736	1	2.736

Σf(Area) = 18.126 ; Common Interval, h = 10º

Converting degree to radian: 1º = $\frac{\pi}{180}$

From equation (11) $Area_{0-30} = \frac{3}{8} h \times \sum f(Area)$

$\therefore Area_{0-30} = 1.1864 m - rad$

Table 6. The area under the righting lever curve (GZ curve) between 0º - 40º

GZ	SM	AREA
O	1	0
3.162	4	12.648
2.167	1	2.167
		14.815

Σf(Area) = 14.815 ; Common Interval, h = 20º

Converting degree to radian: 1º = $\frac{\pi}{180}$

From equation (10) $Area_{0-40} = \frac{1}{3} h \times \sum f(Area)$

$\therefore Area_{0-40} = 1.7238 m - rad$

Table 7. The area under the righting lever curve (GZ curve) between 30º - 40º

GZ	SM	AREA
2.736	**1**	**2.736**
2.455	**4**	**9.82**
2.167	**1**	**2.167**
		14.723

Σf(Area) = 14.723 ; Common Interval, h = 5º

Converting degree to radian: 1º = $\frac{\pi}{180}$

From equation (10): $Area_{30-40} = \frac{1}{3} h \times \sum f(Area)$

$\therefore Area_{30-40} = 0.4283 m - rad$

It is necessary to calculate the maximum moment of statical stability. From equation (3.5): Moment of statical stability = $W \times GM \times \sin\theta^{o}$

Where, W =301.385tonnes; GZ(max) = 3.167m
Moment of statical stability
= 301.385(3.167)
= 954.4833 tonnes-m

Stability Calculations Considering Lightship and Full Tanks

Load case - Lightship and full tanks
Damage Case - Intact
Free to Trim
Specific gravity = 1.025; (Density = 1.025 tonne/m^3)
Fluid analysis method: Use corrected VCG

From the loading sheet we arrived at a final displacement of 239.115tonnes, and solid KG of 3.496m.

Equation (1) and (6) are used to calculate for the righting lever, GZ at different angle of heel.
To check the ship's compliance to minimum IMO requirement, data of the hydrostatic particulars of the ship will be used to construct the curve of statical stability (Graph of GZ against heel angle).

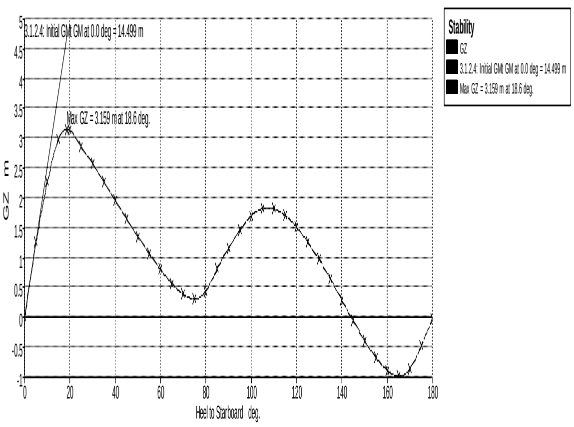

Figure 19: Statical stability curve for load case 2

Table 9. The area under the righting lever curve (GZ curve) between 0º - 30º

GZ	SM	AREA
0	1	0
2.27	3	6.81
3.146	3	9.438
2.586	1	2.586

Σf(Area) = 18.834 ; Common Interval, h = 10º

Converting degree to radian: 1º = $\frac{\pi}{180}$

From equation (11): $Area_{0-30} = \frac{3}{8} h \times \sum f(Area)$

$\therefore Area_{0-30} = 1.2327 m - rad$

Table 8. The area under the righting lever curve (GZ curve) between 0º - 40º

GZ	SM	AREA
O	1	0
3.146	4	12.584
1.976	1	1.976
		14.56

Σf(Area) = 14.56 ; Common Interval, h = 20º

Converting degree to radian: 1º = $\frac{\pi}{180}$

From equation (10): $Area_{0-40} = \frac{1}{3} h \times \sum f(Area)$

$\therefore Area_{0-40} = 1.6941 m - rad$

Table 10. The area under the righting lever curve (GZ curve) between 30º - 40º

GZ	SM	AREA
2.586	1	2.586
2.284	4	9.136
1.976	1	1.976
		13.698

Σf(Area) = 13.698 ;   Common Interval, h = 5°

Converting degree to radian: 1° = $\frac{\pi}{180}$

From equation (10): $Area_{30-40} = \frac{1}{3} h \times \sum f(Area)$

$\therefore Area_{30-40} = 0.3985m - rad$

From equation (.5): Moment of statical stability = $W \times GM \times \sin \theta^{o}$
Where, W = 239.115; GZ (max) = 3.159m
Moment of statical stability = 239.115(3.159) = 755.364tonnes-m

Stability calculation considering just the lightship
Loadcase - Lightship only
Damage Case – Intact
Free to Trim
Specific gravity = 1.025; (Density = 1.025 tonne/m^3)
Fluid analysis method: Use corrected VCG

From the loading sheet we arrived at a final displacement of 210tonnes, and solid KG of 4m.

Equation (1) and (6) are used to calculate for the righting lever, GZ at different angle of heel.
To check the ship's compliance to minimum IMO requirement, data in the hydrostatic particulars of the ship will be used to construct the curve of statical stability (Graph of GZ against heel angle).

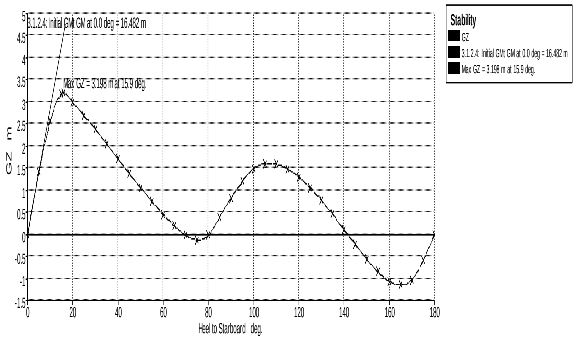

Figure 20: Statical stability curve for loadcase 3

Table 11. The area under the righting lever curve (GZ curve) between 0° - 30°

GZ	SM	AREA
O	1	0
2.557	3	7.671
3.006	3	9.018
2.379	1	2.379

Σf(Area) = 19.068 ;   Common Interval, h = 10°

Converting degree to radian: 1° = $\frac{\pi}{180}$

From equation (11) $Area_{0-30} = \frac{3}{8} h \times \sum f(Area)$

$\therefore Area_{0-30} = 1.248m - rad$

Table 12. The area under the righting lever curve (GZ curve) between 0º - 40º

GZ	SM	AREA
O	1	0
3.006	4	12.024
1.719	1	1.719
		13.743

Σf(Area) = 13.743 ; Common Interval, h = 20º

Converting degree to radian: 1º = $\frac{\pi}{180}$

From equation (10): $Area_{0-40} = \frac{1}{3}h \times \sum f(Area)$

$\therefore Area_{0-40} = 1.5991 m - rad$

Table 13. The area under the righting lever curve (GZ curve) between 30º - 40º

GZ	SM	AREA
2.379	1	2.379
2.051	4	8.204
1.719	1	1.719
		12.302

Σf(Area) = 12.302; Common Interval, h = 5º

Converting degree to radian: 1º = $\frac{\pi}{180}$

From equation (10): $Area_{30-40} = \frac{1}{3}h \times \sum f(Area)$

$\therefore Area_{30-40} = 0.3579 m - rad$

From equation (5): Moment of statical stability = $W \times GM \times \sin\theta^{o}$
Where, W =210; GZ(max) = 3.198m
Moment of statical stability = 210(3.198) = 671.58tonnes-m

Hydrostatic Curves
Damage Case - Intact
Fixed Trim = 0 m (+ve by stern)
Specific gravity = 1.025; (Density = 1.025 tonne/m^3**)**

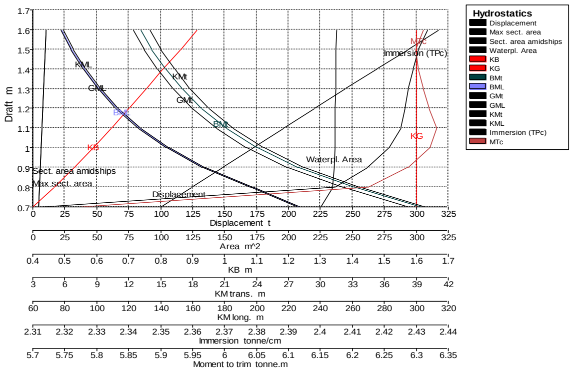

Figure 21: Hydrostatic Curve

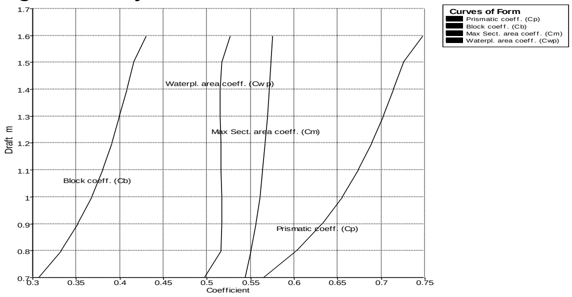

Figure 22: Curve of form

Discussion

This study focuses on understanding the intact stability characteristics of a catamaran under different loading conditions. The study aims to produce better allocation and arrangement plans for machinery, cargo hold, equipment (crane), and stowage and ensure sufficient stability for the ship satisfying the IMO-SOLAS Intact Stability Criteria. The distinctive feature of a catamaran is its higher transverse stability than that of a conventional monohull due to demihull separation. The same data for vessel displacement characteristics, mass, and center of gravity were used to assess static stability and calculate the righting moment available from the upward buoyancy force compared with the overturning moment from the vessel mass operating at its vertical center of gravity (VCG). During the stability analysis, the maximum righting lever (GZmax), when multiplied with the displacement of the ship, gives the value of the maximum heeling moment that the ship can sustain without capsizing. The GZ curve can be obtained easily and the vessel's stability determined. 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 exception for one design criteria, which is the angle of maximum GZ.

Conclusion

In conclusion, the study contributes to the understanding of the intact stability characteristics of a Catamaran under all different loading conditions, helping to produce better allocation and arrangement plans for machinery, cargo hold, equipment (crane), stowage, and ensure sufficient stability for the ship satisfying the IMO-SOLAS Intact Stability Criteria.

References

Dracos, V. (2019).*Intact stability of passenger ships: safety issue or design concern? Neither!.Academia.* https://www.academia.edu/70759355/Intact_stability_of_passenger_ships_safety_issue_or_design_concern_Neither_International Conference on the Stability of Ships and Ocean Vehicles. 1, 17-22 .Liang, Y., Alan B., &Huan Z. R. (2019).*High Speed Catamarans and Multihulls.*Springers.https://doi.org/10.1007/978-1-4939-7891-5.

McVicar, J., Lavroff, J., Davis, M.R., & Thomas G., (2018).*Fluid-Structure Interaction simulation of slam induced bending in large high-speed wave piercing catamarans.* Journal of Fluids and Structures 82, 35-58.

MI News Network. (2019, January 31).*Main Types of Catamarans Used in the Shipping World*.Marine Insight.https://www.marineinsight.com/boating-yachting/main-types-of-catamarans-used-in-the-shippingworld/#:~:text=Origin%20of%20Catamarans,fishing%20boats%20of%20that%20era.https://www.academia.edu/40084942/Intact_Stability.

Soumya, C. (2021, April 5). *Ship Stability – Introduction to Hydrostatics and Stability of SurfaceShips*.Marine Insight.https://www.marineinsight.com/naval-architecture/ship-stability-introduction-hydrostatics-stability-surface-ships/

Tamunodukobipi, D., &Nitonye, S. (2019). *Numerical Analysis of the RAP Characteristics of a Catamaran Vessel for Niger Delta Pliability*.Journal of Power and Energy Engineering. 07. 1-20. 10.4236/jpee.2019.710.