DESIGN & DEVELOPMENT OF MOBILE HARBOUR

NUST, ISLAMABAD

SCHOOL OF MECHANICAL MANUFACTURING ENGINEERING

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ABSTRACT

Recent trends in marine cargo transportation market include continued increase in global container shipping volume and the introduction of mega-sized containerships. It implies that container cargo handling capacity, worldwide, must increase accordingly. A natural consequence of these trends is the need for enhanced port capacity and capability. However, this is not the best solution as it comes with a number of other problems: it brings environmental and large-scale port investment and so on. It is a novel maritime container transport solution that can go out to a ship anchored in the deep water to load/unload containers on sea and take them to their destination ports regardless of their water depth. Thus, our project focuses on the development of mobile harbor and improving its stability using weight slider mechanism. It is a linear actuated mechanism which at least offsets the weight of the containers placed on the ship and reduces the vibration of the ship. The theoretical results show improved stability which means a larger moment arm (measure of stability) at various angles of tilt.

PREFACE

To cater the raising concerns of cargo holding capacity in Marine Transport System and to provide a solution of docking of large cargo ships on shallow sea ports, we are working on the designing and development of small novel maritime container transport system and making it stable enough to go to deep seas and can load and unload containers with ease and comfort. This report includes some literature review and calculations regarding stability of mobile harbor and a self-balancing mechanism system for better heel control during stacking and unstacking of cargo on ships.

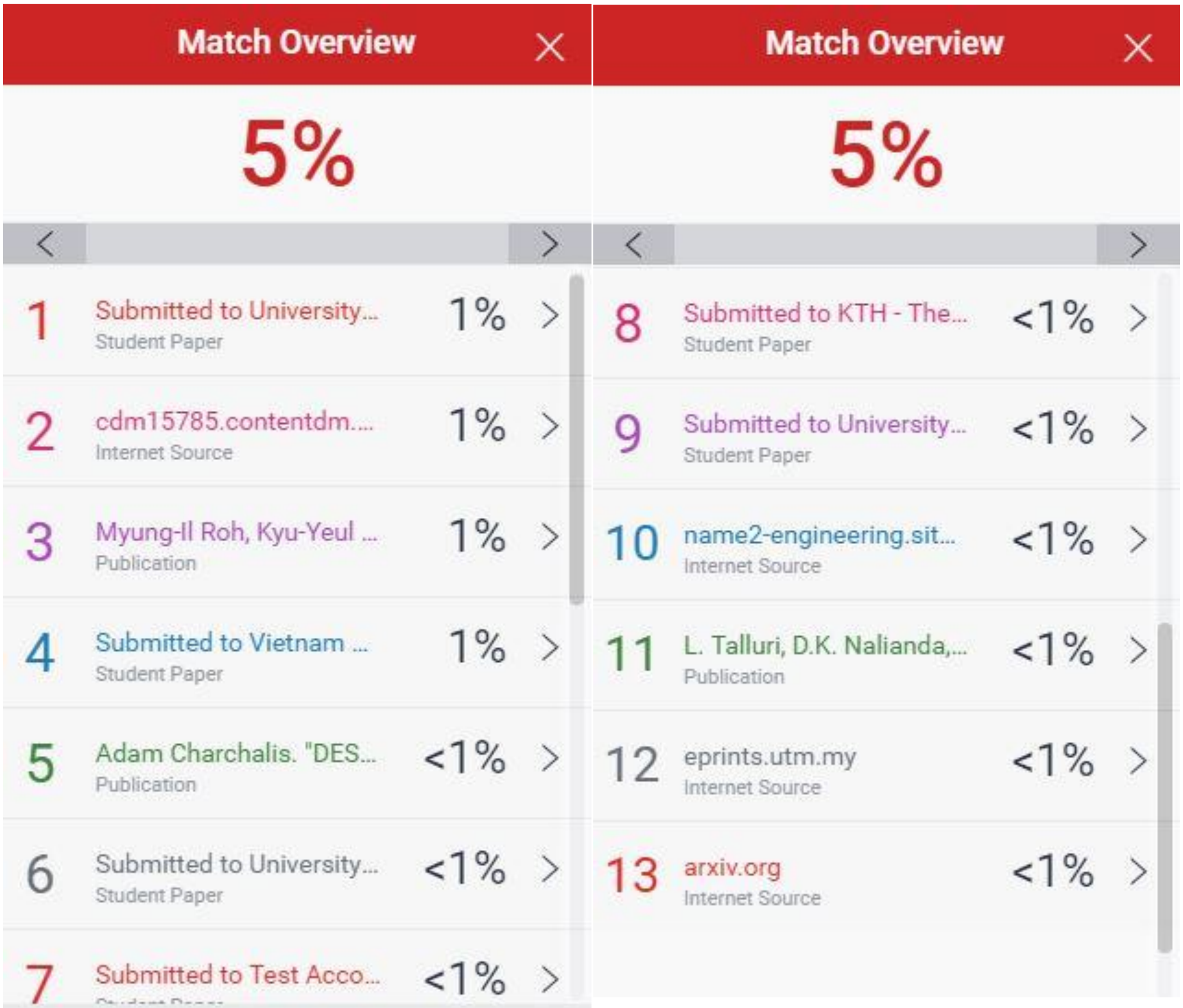
ACKNOWLEDGEMENT

We would like to express our deepest appreciation to all those who provided us the possibility to complete this report. A special gratitude we give to our final year project manager, Mr. Imad, whose contribution in stimulating suggestions and encouragement, helped us to reach the till date progress of our project.

Furthermore, I would also like to acknowledge with much appreciation the crucial role of the staff of SMME, who gave the permission to use all required equipment and the necessary materials and agreed to provide all support for fabrication and tests of our harbour. We have to appreciate the guidance given by other supervisor as well as the panels which include, Mr. Zaib and Mr. Sajjad, especially in our project presentation that has improved our presentation skills thanks to their comment and advices.

We have taken efforts in this project. However, it would not have been possible without the kind support and help of many individuals and staff of SMME. We would like to extend my sincere thanks to all of them.

ORIGINALITY REPORT



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NOMENCLATURE

Symbol	Description	Units
LCB	Longitudinal Center of Buoyancy	m
LCF	Longitudinal Center of Floatation	m
KMt	Metacenter Height from Keel (Transverse)	m
KML	Metacenter Height from Keel (Longitudinal)	m
GM	Metacentric Height	m
GZ	Righting Arm	m
BM	Metacentric Radius	m
KG	Center of Gravity from Keel	m
KB	Center of Buoyancy from Keel	m
∇	Displaced Volume	m^3
I	Second Moment of Inertia	$kg.m^2$
KN	Cross Curve	m
φ	Heel Angle	degrees
TPc	Tonnes Per Centimeter	tonnes/cm
C_b	Block Coefficient	———
R_F	Frictional Resistance	kN
R_{APP}	Resistance of Appendages	kN
R_W	Wave making and Wave breaking resistance	kN
R_B	Additional Pressure Resistance of bulbous bow near water surface	kN
R_{TR}	Additional Pressure Resistance of Immersed Transom Stern	kN
R_A	Model-Ship Correlation Resistance	kN
$1+ k_1$	Form factor describing the various resistance of hull form in Relation to R_F	———
L	Length of water line	m
L_{PP}	Length between perpendiculars	m
B	Breadth Moulded	m
T	Draught	m
T_F	Draught Moulded on F.P	m
T_A	Draught Moulded on A.P	m
∇	Displacement Volume Moulded	m^3
Δ	Displacement Weight	Tonnes
A_{BT}	Transverse bulb area	m^2
h_B	Center of bulb area above keel	m

Symbol	Description	Units
C_M	Midship section coefficient	———
C_{WP}	Water plane area coefficient	———
A_T	Transom area	m^2
S_{APP}	Wetted area appendages	m^2
C_{stern}	Stern shape parameter	———
D	Propeller diameter	m
V	Ship speed	Knots
Z	Number of propeller blades	———
F_n	Froude Number	———
C_P	Prismatic Coefficient	———
c_{1-16}	Ship Coefficients	———
C_B	Block Coefficient	———
i_E	Angle of the waterline at the bow in degrees with reference to the center plane	^{o}
P_E	Effective Power	kW
P_S	Shaft Power	kW
P_D	Propulsive Power	kW
N_G	Efficiency of Gear Box	———
N_M	Mechanical Efficiency of Shaft line	———
N_H	Efficiency of Hull	———
N_R	Rotation Relative Efficiency	———
N_O	Open Water Efficiency	———
C_V	Viscous resistance coefficient	———
C_A	Correlation allowance coefficient	———
P_B	Coefficient for measure for the emergence of the bow	———
C_F	Coefficient of Frictional Resistance	———
T	Propeller Thrust	kN
P	Pitch of propeller	m
S	Stern Area	m^2
[M]	Mass Matrix	———
[A]	Added Mass	———
[X]	Displacement Matrix	———
[B]	Damping Matrix	———
[C]	Stiffness Matrix	———
ω_e	Encounter Frequency	$rad.s^{-1}$
ϕ	Roll Amplitude	m
ω_n	Natural Frequency	$rad.s^{-1}$
ω_d	Damping Frequency	$rad.s^{-1}$
ζ	Damping Ratio	$rad.s^{-1}$

Symbol	**Description**	**Units**
$\partial GM(t)$	Time Varying GM	m
g	Acceleration due to gravity	$m.s^{-2}$
A_n, B_n	Hill Coefficients of GM Variation	———
μ	Linear Damping Coefficient	———
λ	Wavelength	m
α	Frequency Ratio	———
γ	$\partial GM\alpha / GMo$	

SECTION 1 | INTRODUCTION

There are many raising concerns in the Marine Cargo Transport System which will have a direct effect on cargo holding capacity worldwide. Stats show that there is an 11.8% increase in cargo demand in Europe in 2016 with a capacity increase of 5.4%. So, there is a rapid increase in overall container cargo demand internationally. Therefore, it demands large space on ports for cargo handling but there is not enough cargo handling space. There are small ports that don't suffice the cargo capacity demands and that results in time delays in cargo transportation. Other than all of that, due to shallow seas at certain areas, there are many ports in world that are incapable to dock large container ships for loading and unloading of containers. Only small cargo ships can carry load to these ports that results in greater time delays and cargo demands are not met. There is another problem that Cargo Transport companies are dealing with and that is not many countries in the world have multiple ports. So, there is limited port to port transportation and inefficient use of water ways, which results in increase in demand of road transport of containers which in turn is highly expensive.

To counter all these concerns and provide solutions to these problems, different research centres and universities are working on producing smaller, efficient means of water transport vehicles, Mobile Harbours**.** The project aims to deal with recent market needs in marine cargo transportation, while staying economically and environmentally friendly. Mobile Harbour is a novel maritime container transport system. They are time efficient and help increase the handling capacity of a port. They can go out to an anchored ship in the open seas to load or unload containers and transport them regardless of water depth. In addition to these advantages, mobile harbours also ensure efficient use of water ways and can travel to different ports and even cities through river channels, saving cost of road transport of cargo.

We will work on design and development of mobile harbours. We will be studying ways to improve stability of mobile harbours and perform stability analysis on CAD models. We will also be fabricating a prototype of mobile harbours and perform different tests on it, drawing stability and moment curves. We will study pre-existing ways to improve stability and implement it on our model, making it stable enough to load and unload containers with ease and comfort at sea. In addition to all of that, we are working on a motor driven linear actuator system to improve stability of ships and for better control during loading and unloading of containers.

Figure 1: Mobile Harbour

SECTION 2 | LITERATURE REVIEW

2.1 | PRELIMINARY DESIGN

Determining main dimensions of a container ship is based on design assumptions, which indicate at least the number of TEU containers, required ship speed, resistance criteria and restrictions within a given area of sailing. The main hull dimensions are displacement D, length L, breadth B, draught T, their combinations and block coefficient.

The main dimensions have a great impact on developing the ships resistant performance. It is important to limit the total ship resistance especially when TEU number carried by one vessel is increasing. That resistance depends on the operational speed expressed by Froude number. Resistance criteria should be taken into consideration with hull unsinkability, stability and integrity conditions. That is why precise determination of vessel main dimensions and basic correlations defining their properties is absolutely crucial in the whole vessel design.

In our case design restriction was draught which was not to exceed 6.5 m while maximizing the number of TEU containers. According to (1) deadweight/displacement ratio for container ships should be approximately 0.65. One of the most important main ship dimensions affecting its hull integrity, displacement, and stability is the length between perpendiculars. The selected length of the ship depends on the recommended fineness ratio L/D, which should be within the range 5.5-6.5. The length of a ship also depends on Froude number, whose value essentially determines the value of wave resistance. The maximum wave resistance values occur with Fn = 0.5; 0.22-0.23 and 0.32 (2). Thus, Froude number of 0.24 was chosen. The breadth of a container ship primarily depends on the number of rows of transported containers. In terms of ship resistance, it is important to ensure proper relation between the ship length and breadth. For cargo ships the L/B ratio is in range 5.7-7.5 (1). Hull draught significantly affects ship resistance, stability and unsinkability. B/T ratio for cargo ships should be 2.0-2.5 (3) (1), and the T/H ration should be 0.7-0.8 (3) (1). Hull integrity and stability considerably influence determining its main dimensions. It is important to maintain an appropriate relation between hull length and breadth, and side height. In terms of hull integrity L/H = 10-13 (1) and in terms of stability, the relation between ship breadth and side height B/H = 1.9 (1). Power is estimated using admiralty constant whose value ranges form 500-600 for cargo ships (4). Optimum Hull coefficients were found using different relations from (1) and (2).

2.2 | TOTAL RESISTANCE AND POWER PREDICTION

At the initial design stage, the estimate of the total hull resistance RT can be done mainly using methods based in statistical analysis. These methods were developed through regression analysis of random model experiments and full-scale data (5). Some of the methods include Oossanen (small high-speed displacement craft), Keunung and Gerritsma (planing hull forms), Savitsky(planing hull forms), Sabit (Series 60), Keller, Harvald Holtrop & Mennen (1978, 1980) (6) . Since method of Holtrop & Mennen has proved to give good results for merchant ships it was used to estimate Total resistence. According to Holtrop & Mennen the total resistence is given as follows:

$$R_{Total} = R_F(1 + k_1) + R_{APP} + R_w + R_{\boldsymbol{B}} + R_{\boldsymbol{TR}} + R_{\boldsymbol{A}}$$

Each parameter was calculated as per the relations given in (5). Further details are discussed in methodology section. The propulsive power depends on different efficiencies including Efficiency of the gear Box(Ng), Mechanical efficiency of the shaft line(Nm), Efficiency of the hull (Nh), Rotation relative efficiency Nr, Open water efficiency of the propeller (No). Standard values of Ng, Nm, Nc, Nr, No are 0.99,0.995,1.07,1.01 and 0.32 respectively (6). The propulsive power was estimated using the relationship given in (6).

2.3 | STABILITY OF SHIP

The stability of the ship means whether the ship will be able to move massive distances under various conditions of sea like waves and wind. It starts with the basic principle of floatation and then to more intricate and advanced concepts of transverse and longitudinal stability. It becomes quite significant when the ship tilts in either transverse or longitudinal direction. Moreover, container ships are even stable at thirty to forty degrees of tilt about its center of gravity. The literature material for container ship stability was available in books and online courses which provided enough help in determining the stability for our proposed ship design.

The ‘Principle of Floatation’ or ‘Archimedes’ Law’ was the basis for determining the buoyancy of our ship model or how much weight can our ship lift if its draft is given. Archimedes’ Law states that anybody completely or partially submerged in a fluid (gas or liquid) at rest is acted upon by an upward, or buoyant, force the magnitude of which is equal to the weight of the fluid displaced by the body. Its references were found in two books named 'Ship Hydrostatics and Stability by Adrian Biran and Ruben Lopez-Pulido' and 'Merchant Ship Stability by H. J. Pursey' in Chapter 2 and Chapter 1 respectively. It means the weight of the floating object will be equal to the weight of the fluid displaced. (7) (8)

It was important since it will help in calculating the tonnage weight the modelled ship can carry and what will be its draft. Subsequently, using the dimensions of the ship and tonnage weight, number of TEUs (containers) that can be carried by the ship model can be calculated. This also helps in choice of various ship types with different dimensions. The formula of Archimedes' Law is given below:

$$Weight\ of\ Body = Weight\ of\ Fluid\ displaced$$

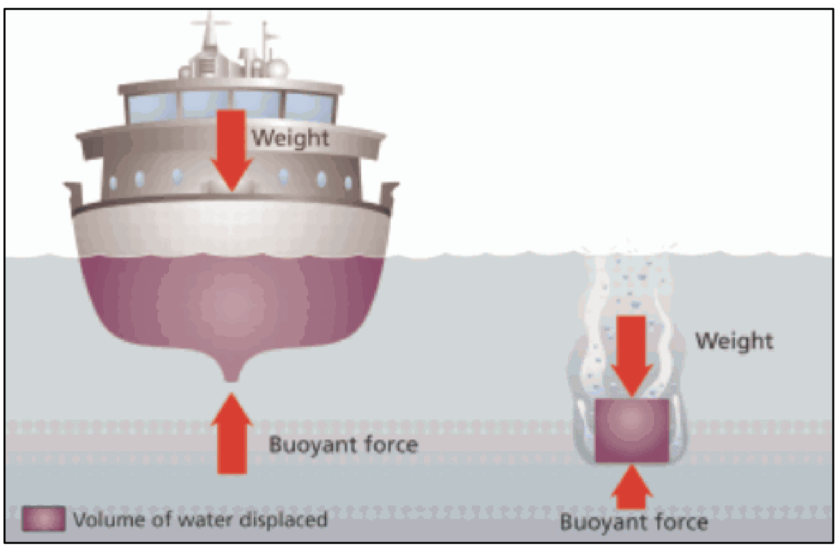


Figure 2: Archimede's Principle

Secondly, several terminologies were studied from the same two books named 'Ship Hydrostatics and Stability by Adrian Biran and Ruben Lopez-Pulido' and 'Merchant Ship Stability by H. J. Pursey' from Chapter 2 and Chapter 6 respectively. For instance, Center of Gravity of the ship which is the point at which the whole weight of the ship is assumed to be acting and Center of Buoyancy is the point at which the upward buoyancy force is acting. Another terminology is Metacenter which is the theoretical point at which an imaginary vertical line passing through the center of buoyancy and center of gravity intersects the imaginary vertical line through a new center of buoyancy created when the body is displaced, or tipped, in the water. These three are mandatory points upon which the stability of the ship depends. (8)

Furthermore, online free courses were also quite helpful in laying the grounds for advanced concepts. The courses were about Ship Hydrostatics (Marine Schools). One of the concept is about the Metacentric Height which is commonly known as 'GM'. As the name suggests it is the distance between the Center of Gravity and Ship's Metacenter. According to the books and the courses, the GM has to be greater than one otherwise the ship will sink. It means when the GM is less than one the ship experiences moment that causes capsizing. The three types of equilibrium mentioned were stable equilibrium, unstable equilibrium and neutral equilibrium (9). All these concepts aided in determining whether the ship is in stable equilibrium or if the ship will sink or not. The formula for calculating the GM is given below:

$$GM = KB + BM - KG$$

In this above formula KB and KG are the Center of Buoyancy and Center of Gravity from the Keel of the ship. BM is the Metacentric Radius which is another important terminology in the ship stability calculation. As its name suggest it is the distance between the Center of Buoyancy and Ship's Metacenter. It is required in calculating the Metacentric Height (GM), but BM is calculated through the following formula as given the above-mentioned books (8) (7).

$$Metacentric\ Radius = \frac{Second\ Moment\ of\ Inertia}{Displaced\ Volume}$$

$$BM = \frac{I}{\nabla}$$

Both Metacentric Height and Radius are calculated in the transverse and longitudinal direction to quantify the transverse and longitudinal stability of the ship. One can refer to these topics in Chapter 5 and Chapter 12 of the book 'Merchant Ship Stability by H. J. Pursey'. However, transverse stability is critical as its moment of Inertia is drastically less than that of longitudinal stability. As mobile harbor is in simple terms highly stable ship

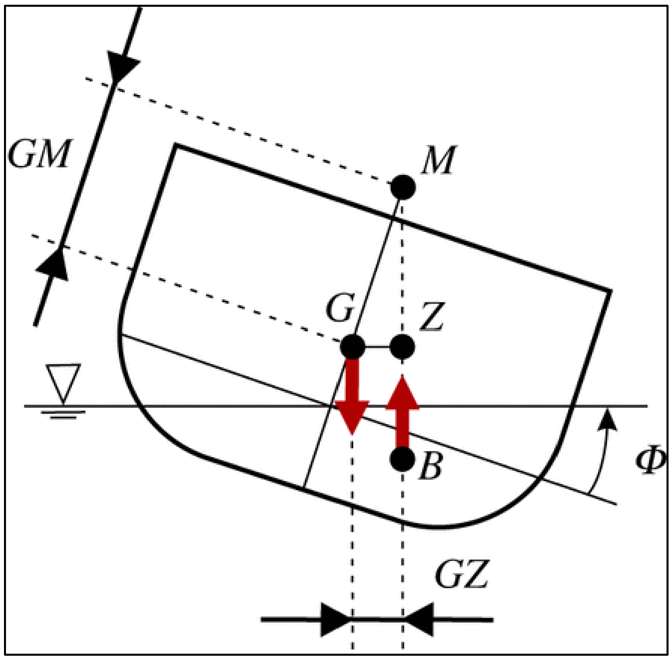


Figure 3: Ship Stability

for container loading and unloading all these concepts are vital in understanding the dynamics of the problem.

Lastly, the most important finding is the 'Static Stability Curves' which shows the righting moment arm at different angles of heel. It is commonly known as the 'GZ Curve'. One can find its references in many places but in particular one can refer to the books named 'Ship Hydrostatics and Stability by Adrian Biran and Ruben Lopez-Pulido' and 'Merchant Ship Stability by H. J. Pursey. Righting moment arm specifies the moment acting on the ship to either bring the ship to its upright position or capsize it. Then there are other terms like 'Angle of Deckage Immersion' and 'Angle of Vanishing Stability' which can be identified by looking at the GZ curve. GZ curve also specifies the range of heel angle for which the righting arm is positive. It means the ship will return to its upright position if no external force is acting on it. Similarly, there is a term called 'Angle of Lol' which is the permanent angle of heel and a defect in the ship's development (8) (7).

The book describes the two methods to find the Static Stability Curve as well. One is through using the KN curves and the other is through using the wall sided formula. KN curves are also called Cross curves. The graph clearly shows various curves of KN at different angles of heel and tonnage weight (9). The formula for finding the GZ through KN curves is given below:

$$GZ = KN - KG * Sin(\varphi)$$

The wall sided formula can be divided into two. One is for small angles of Heel ranging from zero to seven degrees and the other is for large angles of Heel that is greater than seven degrees. The assumption for using this formula is that the ship has to be wall sided. The formula for small angles of heel is given below:

$$GZ = GM * Sin(\varphi)$$

Similarly, the formula for large angle of heel is given below:

$$GZ = Sin(\varphi) * \left(GM + \frac{1}{2} * BM * Tan^2(\varphi)\right)$$

Hence, the static stability curves are the focal point of finding the stability of Mobile Harbor at different angles of inclination and determining how much the stability improves when weight-slider mechanism is used.

2.4 | Parametric Roll

Waves always exist, even if very small and they can influence ship stability severely. Ships can capsize in head seas—that is waves travelling against the ship—and especially in following seas—that is waves travelling in the same direction with the ship. Waves severly affect the roll amplitude of the ship. Chantrel (1984) studied the large-amplitude motions of an offshore supply buoy and attributed them to the variation of properties in waves leading to the phenomenon of parametric resonance (8). France e``t al. (2001) analyze an accident that occurred in the north Pacific to a container ship of 262 m length between perpendiculars. A severe storm caused angles of roll of 35◦ to 40◦ (8).

Parametric resonance is a new mode of ship capsizing; the first are due to insufficient metacentric height and to insufficient area under the righting-arm curve. Parametric systems are a class of time varying systems. Parametric vibrations are vibrations that result from the time variation of coefficients (mass, damping, stiffness) in the equation of motion. A certain class of parametric systems which have harmonic variation of stiffness (influence of waves on ship stability) can be described by the Mathieu's equation[8]. For non-harmonic but periodically varying stiffness there is a different class of differential equations called the Hill's equation. The Hill's equation utilizes the method of Fourier fit to represent the non-harmonic variation of stiffness (10). If a Mathieu's equation is used for representing a non-harmonic variation of stiffness then we are essentially considering only the first harmonic and neglecting higher order harmonics of the Fourier expansion (10).

For Mathieu equation, 2 pie solution and 4 pie solution are as following in Matrix form:

$$\begin{bmatrix} \alpha & \frac{\gamma}{2} & 0 & 0 & 0 & \dots & 0 \\ \gamma & \alpha-1 & \mu & \frac{\gamma}{2} & 0 & \dots & 0 \\ 0 & \mu & \alpha-1 & 0 & \frac{\gamma}{2} & \dots & 0 \\ 0 & \frac{\gamma}{2} & 0 & \alpha-4 & \mu & \frac{\gamma}{2} & 0 \\ .. & & & & & & .. \end{bmatrix}$$

$$\begin{bmatrix} \alpha-\frac{1}{4}+\frac{\gamma}{2} & \frac{\mu}{2} & \frac{\gamma}{2} & 0 & 0 & \dots & 0 \\ \frac{\mu}{2} & \alpha-\frac{1}{4}-\frac{\gamma}{2} & 0 & \frac{\gamma}{2} & 0 & \dots & 0 \\ \frac{\gamma}{2} & 0 & \alpha-\frac{9}{4} & \frac{3\mu}{2} & \frac{\gamma}{2} & \dots & 0 \\ 0 & \frac{\gamma}{2} & -\frac{3\mu}{2} & \alpha-\frac{9}{4} & 0 & \frac{\gamma}{2} & 0 \\ .. & & & & & & .. \end{bmatrix}$$

For Hill equation, 2 pie solution and 4 pie solution are as following in Matrix form:

$$\begin{bmatrix} \alpha - \frac{1}{4} + \frac{\gamma A_1}{2} & \frac{\gamma B_1}{2} + \frac{\mu}{2} & \frac{\gamma(A_2 + A_1)}{2} & \frac{\gamma(B_2 + B_1)}{2} & \frac{\gamma(A_2 + A_3)}{2} & \cdots & 0 \\ \gamma B_1 - \frac{\mu}{2} & \alpha - \frac{1}{4} - \frac{\gamma A_1}{2} & \frac{\gamma(B_2 - B_1)}{2} & \frac{\gamma(A_2 - A_1)}{2} & \frac{\gamma(B_3 - B_2)}{2} & \cdots & 0 \\ \frac{\gamma(A_2 + A_1)}{2} & \frac{\gamma(B_2 - B_1)}{2} & \alpha - \frac{9}{4} + \frac{\gamma A_3}{2} & \frac{\gamma B_3}{2} + \frac{3\mu}{2} & \frac{\gamma(A_1 + A_4)}{2} & \cdots & 0 \\ \frac{\gamma(B_1 + B_2)}{2} & \frac{\gamma(A_1 - A_2)}{2} & \frac{\gamma B_3}{2} - \frac{3\mu}{2} & \alpha - \frac{9}{4} - \frac{\gamma A_3}{2} & \frac{\gamma(B_4 - B_1)}{2} & \cdots & 0 \\ .. & & & & & & .. \end{bmatrix}$$

$$\begin{bmatrix} \alpha & \frac{\gamma A_1}{2} & \frac{\gamma B_1}{2} & \frac{\gamma A_2}{2} & \frac{\gamma B_2}{2} & \cdots & 0 \\ \gamma A_1 & \alpha - 1 & \frac{\gamma B_2}{2} + \mu & \frac{\gamma(A_3 + A_1)}{2} & \frac{\gamma(B_3 + B_1)}{2} & \cdots & 0 \\ \gamma B_1 & \frac{\gamma B_2}{2} - \mu & \alpha - 1 - \frac{\gamma A_2}{2} & \frac{\gamma(B_3 - B_1)}{2} & \frac{\gamma(A_3 - A_1)}{2} & \cdots & 0 \\ \gamma A_2 & \frac{\gamma(A_3 + A_1)}{2} & \frac{\gamma(B_3 - B_1)}{2} & \alpha - 4 + \frac{\gamma A_4}{2} & 2\mu + \frac{\gamma B_2}{2} & \cdots & 0 \\ .. & & & & & & .. \end{bmatrix}$$

There are transition values for which the Mathieu's equation has solutions that consist of or periodic solutions. Hence it is appropriate to assume a Fourier series representation of the or periodic solution to determine the transition values. This method is the Hill's infinite determinant method. The Hill's infinite determinant method is a more robust method (10). A general practice is to approximate a non-harmonic variation of GM by a harmonic one so as to use the Mathieu's equation for prediction. It is seen that the maximum variation in GM occurs when the wave length is close to the ship length (10) (8), as a result analysis will be carried out for the critical case of wave length equal to the ship length.

Stability charts called Ince-Strutt diagram (van der Pol and Strutt, 1928) can be developed for each of the equations (obtained by solving the determinant of matrix) which define the stable and unstable region in the parameter space. For a ship, unstable response means capsizing These charts can serve as a tool in determining the stability of the system. They also provide details on the type of parametric resonance causing the instability. It is a very common to see that a system susceptible to parametric vibration tends to exhibit the phenomenon when the excitation frequency (frequency of variation of the parameter) is twice the natural frequency of the system (8) (10). This is called the primary resonance in the parametric system.

For the damped Mathieu's equation, the curves are lifted off from the axis due to the presence of the damping coefficient. Damping in general can be thought to reduce the unstable region of the stability chart (10). Thus, linear damping tends to reduce the unstable region for smaller values of and increase the unstable region for higher values (10).

The effects of forward speed of the vessel on roll motion are also investigated. The effect of forward speed is similar to that of Doppler effect (10). Due to the forward speed of the vessel, depending on the direction of wave approach, the vessel tends to encounter waves at different frequencies. As parametric roll is sensitive to encounter frequency (8), a change in encounter frequency can instigate parametric roll, increase or decrease the roll amplitude and can even kill the motion depending on the frequency of encounter.

Mathematical Equation:

$$[M + A(w)]\left[\ddot{X}\right] + [B(w)]\left[\ddot{X}\right] + [C][X] = [F]$$

For zero speed case, by selecting a different ship fixed coordinate system as the origin we can eliminate the added inertia coupling effects. If coupling terms in the matrix are negligible the roll equation of motion completely decouples from sway and yaw motion. For the head sea condition there is no direct external forcing in the roll direction, and equation of motion can be represented as

$$\left(I_{44} + A_{44}(\omega_D)\right)\ddot{\phi} + \left(B_{44}(\omega_D)\right)\dot{\phi} + C\phi = 0$$

$$\left(I_{44} + A_{44}(\omega_D)\right)\ddot{\phi} + \left(B_{44}(\omega_D)\right)\dot{\phi} + \nabla gGM\phi = 0$$

$$\left(I_{44} + A_{44}(\omega_D)\right)\ddot{\phi} + \left(B_{44}(\omega_D)\right)\dot{\phi} + \nabla g(GM_o + \partial GM(t))\phi = 0$$

It is well known that the ship stability in waves is quite different from that of the calm water condition. This is due to the fact that the wave profile tends to change the underwater hull shape and the shape of water plane which in turn affects the restoring arm and the restoring moment.

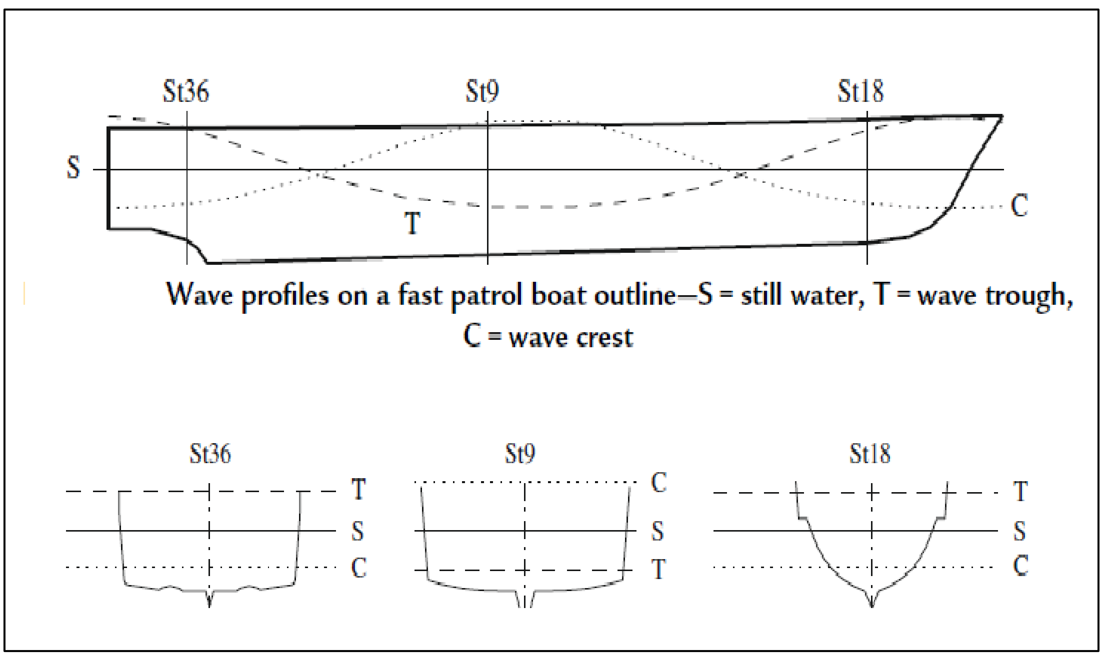
The righting arm with the wave crest position at amidships tends to be smaller than the still water condition and that due to wave trough at amidships tends to be larger than the still water level. With the wave crest amidships, there is a loss of water plane area at the bow and aft sections resulting in a reduction in the water plane inertia. Due to the wall sided shape of the midship sections there is no significant loss of water plane area amidships. In the case of wave trough amidships, there is an increase in the water plane area at the bow and stern due to the flare above the water line.

Time varying GM may be expressed as a variation from a still water

$$GM(t) = GM + \partial GM(t)$$

Thus, the general equation of motion in roll

$$\left(I_{44} + A_{44}(\omega_D)\right)\ddot{\phi} + \left(B_{44}(\omega_D)\right)\dot{\phi} + \nabla g\left(GM_o + \partial GM(t)\right)\phi = 0$$



Wave profiles on a fast patrol boat outline—S = still water, T = wave trough, C = wave crest

Figure 4:Comparison of Wave Crest/Trough Variation

$$\tau = \omega t \, , \omega_D = \sqrt{\frac{g\Delta GM_o}{(I + A_{44}(w_D))}}$$

$$\alpha = (\frac{\omega_D}{\omega})^2$$

$$\mu = \frac{B_{44}(\omega_D)}{\big(I + A_{44}(\omega_D)\big)\omega}$$

If GM variations are considered in Cosine form then Mathieu Equation becomes

$$\frac{d^2}{d\tau^2}\phi + \mu\frac{d}{d\tau}\phi + \left(\alpha + \frac{\partial GM(t)}{GM_o}\alpha\right)\phi = 0$$

$$\partial GM(t) = \partial GM \cos\tau$$

$$\gamma = \frac{\partial GM}{GM_o}\alpha$$

$$\frac{d^2}{d\tau^2}\phi + \mu\frac{d}{d\tau}\phi + (\alpha + \gamma cos\tau)\phi = 0$$

GM variation can also be represented in the following form:

$$\partial GM(t) = \sum_{n=0}^{\infty}(C_n\cos(n\tau) + \ S_n\sin(n\tau))$$

Thus, the equation becomes following which is also called Hill equation:

$$\frac{d^2}{d\tau^2}\phi + \mu\frac{d}{d\tau}\phi + \left(\alpha + \gamma\sum_{n=1}^{\infty}(A_n\cos(n\tau) + \ B_n\sin(n\tau))\right)\phi = 0$$

SECTION 3 | METHODOLOGY

Flowchart summarizes our analysis procedure of Parametric roll on regular waves.

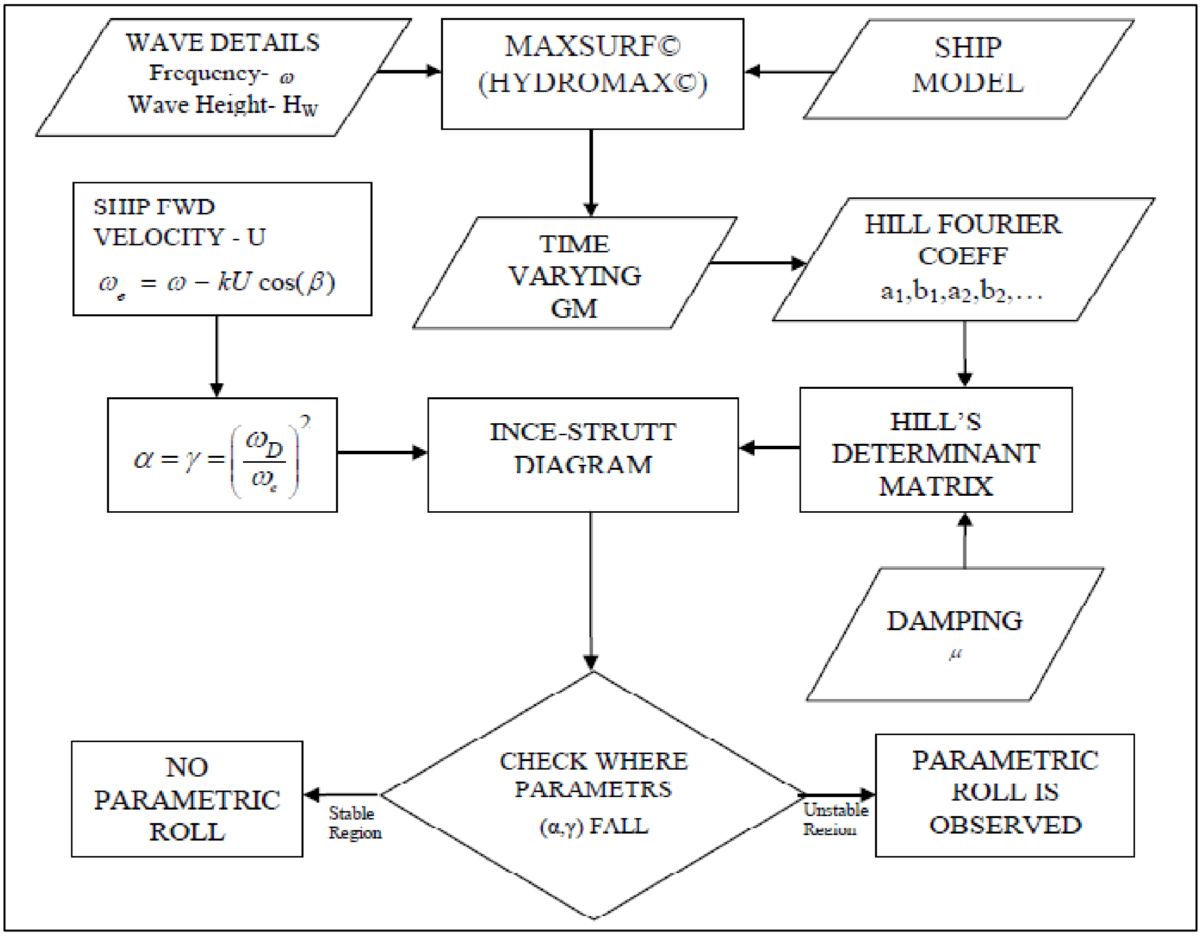


Figure 5: Methodology Flowchart

3.1 | Preliminary Ship Design

Various Ships were studied and a suitable DWT was selected.

Deadweight/Displacement of 0.7 was selected from the table below:

	1	2	3	4	5	6
Ship type	Limits		DWT/Δ (%)	W_{ST}/W_L (%)	W_{OT}/W_L (%)	W_M/W_L (%)
	Lower	Upper				
General cargo ships (t DWT)	5,000	15,000	65–80	55–64	19–33	11–22
Coasters, cargo ships (GRT)	499	999	70–75	57–62	30–33	9–12
Bulk carriers[a] (t DWT)	20,000	50,000	74–85	68–79	10–17	12–16
	50,000	200,000	80–87	78–85	6–13	8–14
Tankers[b] (t DWT)	25,000	120,000	78–86	73–83	5–12	11–16
	200,000	500,000	83–88	75–88	9–13	9–16
Containerships (t DWT)	10,000	15,000	65–74	58–71	15–20	9–22
	15,000	165,000[c]	65–76	62–72	14–20	15–18
Ro-Ro (cargo) (t DWT)	$L \cong 80$ m	16,000 t	50–60	68–78	12–19	10–20

Figure 6: Different Ship Characteristics

Using Deadweight/Displacement of 0.7 mass displacement was calculated.

Where mass displacement is:

$$Mass\ Displacement = Dead\ Weight\ (DWT) + Mass\ of\ Hull$$

Since we know the overall mass displacement, volume displacement was calculated using the following relation

$$Mass = Density * Volume$$

Length (L) was calculated using the following relation:

$$L \quad = \quad (Volume * 1/3)\ x\ 5$$

Breadth (B) was estimated using the following relationship:

$$B = \frac{L}{4 + 0.009\ x\ (L + 42)}$$

Fn of 0.24 was selected considering the numbers when local maxima of wave resistance occur. The maxima can be observed in range 0.22-0.23.

Cb was calculated using the following relation:

$$Cb = 1.2 - 2.378\ x\ Fn$$

Draught (T) was calculated using:

$$T = \frac{Volume}{L\ x\ B\ x\ Cb}$$

Midship coefficient (Cm) was calculated as:

$$Cm = 0.928 + 0.08\ x\ Cb$$

Waterline coefficient was calculated from the following relationship:

$$Cwl = 0.3333333\ x\ (1 + 2\ x\ Cb)$$

Prismatic coefficient was calculated using the relation:

$$Cp = \frac{Cb}{Cm}$$

Wetted surface area was calculated using the following relation:

$$S = Lx\ W\ (1.7 + Cb\ x\ \frac{B}{T})$$

Power was predicted by admiralty formula:

$$P_B = \frac{\Delta^{\frac{2}{3}} V^3}{C}$$

The value of C was chosen as 600 based on the following fact:

general cargo ships	400–600
bulker and tanker	600–750
reefer	550–700
feedership	350–500
warship	150

Figure 7: Admiralty Constant

These coefficients were then compared to the standard ship coefficients given below to check the validity:

Ship type	Hull form coefficients				Ratios of main dimensions		
	C_P	C_M	C_B	C_{WP}	L_{PP}/B	B/T	$L_{PP}/\nabla^{1/3}$
Fast seagoing cargo ships	0.57–0.65	0.97–0.98	0.56–0.64	0.68–0.74	5.7–7.8	2.2–2.6	5.6–5.9
Slow seagoing cargo ships	0.66–0.74	0.97–0.995	0.65–0.73	0.80–0.86	4.8–8.5	2.1–2.3	5.2–5.4
Coastal cargo ships	0.69–0.73	−0.985	0.58–0.72	0.78–0.83	4.5-5.5	2.5–2.7	4.2–4.8
Small short sea passenger ships	0.61–0.63	0.82–0.85	0.51–0.53	0.65–0.70	5.8-6.5	3.3–3.9	6.3–6.6
Ferries	0.53–0.62	0.91–0.98	0.50–0.60	0.69–0.81	5.9–6.2[a] 5.2–5.4[b]	3.7–4.0	6.2–6.9[a] 5.7–5.9[b]
Fishing vessels	0.61–0.63	0.87–0.90	0.53–0.56	0.76–0.79	5.1–6.1	2.3–2.6	5.0–5.4
Tugboats	0.61–0.68	0.75–0.85	0.50–0.58	0.79–0.84	3.8–4.5	2.4–2.6	4.0–4.6
Bulk carriers	0.79–0.84	0.990–0.997	0.72–0.86	0.88–0.92	5.0–7.1[a]	2.1–3.2	4.7–5.6

Figure 8: Various Ship Characteristics

Velocity of the ship was selected from the following graph:

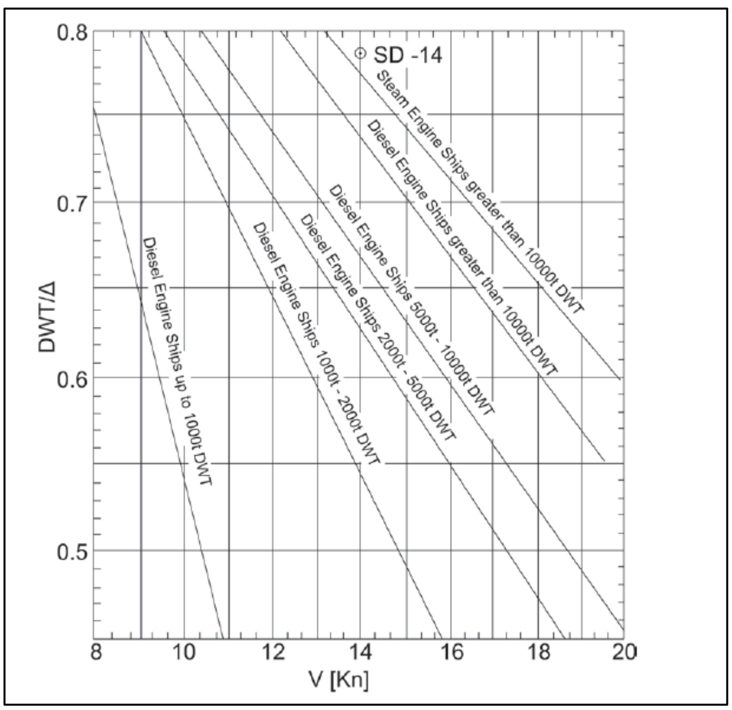


Figure 9: Velocity Variations

3.2 | Resistance Prediction

The total resistance of a ship has been subdivided into:

$$R_{Total} = R_F(1 + k_1) + R_{APP} + R_w + R_{\boldsymbol{B}} + R_{\boldsymbol{TR}} + R_{\boldsymbol{A}}$$

Since RAPP, RB and RTR accounts very little to the resistance the equation becomes:

$$R_{Total} = R_F(1 + k_1) + R_w + R_{\boldsymbol{A}}$$

$$1 + k_1 = c_{13}\{0.93 + c_{12}\left(\frac{B}{L_R}\right)^{0.92497}\left(0.95 - C_p\right)^{-0.521448}(1 - C_p + 0.0225\, lcb)^{0.6906}\}$$

LR in the following formulae is calculated as

$$\frac{L_R}{L} = 1 - C_p + 0.06C_p\frac{lcb}{(4C_p - 1)}$$

The coefficient c12 defined as:

$$c_{12} = (\frac{T}{L})^{0.2228446} \quad when\ T/L > 0.05$$

$$c_{12} = 48.20\left(\frac{T}{L} - 0.02\right)^{2.078} + 0.479948 \quad when\ 0.02 < \frac{T}{L} < 0.05$$

$$c_{12} = 0.479948 \quad when \frac{T}{L} < 0.02$$

coefficient c13 accounts for the specific shape of the afterbody and is related to the coefficient Cstern according to:

$$c13 = l + 0.003 * Cstern$$

Afterbody form	C_{stern}
V-shaped sections	– 10
Normal section shape	0
U-shaped sections with Hogner stern	+ 10

Figure 10: Cstern Values

The wave resistance is determined from:

$$R_w = c_1 c_2 c_5 \nabla \rho g \exp\{m_1 F_n^d + m_2 \cos(\lambda F_n^{-2})\}$$

$$c_1 = 2223105 c_7^{3.78613} \left(\frac{T}{B}\right)^{1.07961} (90 - i_E)^{-1.37565}$$

$$c_7 = 0.229577 \left(\frac{B}{L}\right)^{0.3333} \quad when \frac{B}{L} < 0.11$$

$$c_7 = \frac{B}{L} \quad when \; 0.11 < \frac{B}{L} < 0.25$$

$$c_7 = 0.5 - 0.0625 \frac{L}{B} \quad when \frac{B}{L} > 0.25$$

$$c_2 = \exp\left(-1.89\sqrt{c_3}\right)$$

$$c_5 = 1 - \frac{0.8 \, A_T}{BTC_M}$$

$$\lambda = 1.446 \, C_p - 0.03 \frac{L}{B} \quad when \frac{L}{B} < 12$$

$$\lambda = 1.446 \, C_p - 0.36 \quad when \frac{L}{B} > 12$$

$$m_1 = 0.0140407 \frac{L}{T} - \frac{1.75254 \nabla^{\frac{1}{3}}}{L} - 4.79323 \frac{B}{L} - c_{16}$$

$$c_{16} = 8.07981 \, C_P - 13.8673 C_P^2 + 6.984388 \, C_P^3 \quad when \; C_P < 0.80$$

$$c_{16} = 1.73014 - 0.7067 \, C_P \quad when \; C_P > 0.80$$

$$m_2 = c_{15} C_P^2 \exp(-0.1 \, F_n^{-2})$$

where c15 is given by

$$c_{15} = -1.69385 + \frac{\frac{L}{\nabla^{\frac{1}{3}}} - 8}{2.36} \qquad 512 < \frac{L^3}{\nabla} < 1727$$

The half angle of entrance i.e. is the angle of the waterline at the bow in degrees with reference to the center plane and is calculated as:

$$i_E = 1 + 89 \exp\{-\left(\frac{L}{B}\right)^{0.80856} (1 - C_{WP})^{0.30484} (1 - C_P - 0.0225\, lcb)^{0.6367} \left(L_{\frac{R}{B}} \right)^{0.34574} \left(\frac{100\nabla}{L^3}\right)^{0.16302} \}$$

RA model-ship correlation resistance is calculated as:

$$R_A = \frac{1}{2} \rho v^2 S C_A$$

$$C_A = 0.006(L + 100)^{-0.16} - 0.00205 + 0.003 \sqrt{\frac{L}{7.5}} C_B^4 c_2 (0.04 - c_4)$$

$$c_4 = \frac{T_F}{L}$$

Power was calculated from the following relations:

$$PD = \frac{Pe}{\text{Ng x Nm x Nh x Nr x No}}$$

$$Where\ Pe\ =\ V\ x\ Rtotal$$

$$Ng = 0.99$$

$$Nm = 0.995$$

$$Nh = 1.07$$

$$Nr = 1.01$$

$$No = 0.32$$

3.3 | GM Variations

The following assumptions are made in the estimation of GM in regular waves using the hydrostatic software (MAXSURF).

1. The displacement of the vessel is assumed to be constant i.e. the vessel is hydrostatically balanced over the wave.
2. The effects of heave and pitch motion on the wave profile is neglected.
3. The wave elevation effects are considered to be the primary cause of GM variation.

The GM is estimated for 20 positions of wave crest along the vessels and we obtained coefficients to represent the GM variation. The time varying GM is represented as follows:

$$GM(t) = GM_{mean} + \sum_{j=1}^{4}(C_n \cos(\omega\tau) + \ S_n \sin(\omega\tau)$$

The Fourier coefficients of the Hill's equation in Matrix are obtained from the coefficients in using the following relationship:

$$A_1 = \frac{C_1}{GM_{mean}} \qquad B_1 = \frac{S_1}{GM_{mean}}$$

$$A_2 = \frac{C_2}{GM_{mean}} \qquad B_2 = \frac{S_2}{GM_{mean}}$$

$$A_3 = \frac{C_3}{GM_{mean}} \qquad B_3 = \frac{S_3}{GM_{mean}}$$

$$A_4 = \frac{C_4}{GM_{mean}} \qquad B_4 = \frac{S_4}{GM_{mean}}$$

Solving Determinant and Drawing Stability Curves (add equation and curves diagram). By setting the Hill determinant to zero we obtain the implicit relationship between and α, γ and μ. These equations were solved for different values of μ. By plotting these relations on Matlab, we obtained the stable and unstable region.

3.4 | Calculating Frequency of Encounter

The wavelength is taken equal to ship length [8] [7] b/c that's the critical length that can adversely affect the parametric roll. In wave theory, it is shown that the relationship between wave length and wave circular frequency, in water of infinite depth, is [8]

$$\lambda = \frac{2\pi}{\omega_w^2}$$

From this wave circular frequency is calculated and the frequency of encounter is calculated from the following equation [8]

$$\omega_E = \omega_w - \frac{\omega_w^2}{g} v\, cos\alpha$$

α the X axis of ince strut diagram is calculated as follows

$$\alpha = (\frac{\omega_D}{\omega_e})^2$$

3.5 | STABILITY OF SHIP

For all the intricate calculations, Marine or Hydrostatics software called ‘MAXSURF’ is used. This software is useful in developing the hull surfaces according to appropriate hydrostatic coefficients and then carry out various simulations under different conditions (11).

The stability calculations start with the manipulation of weights. It means the amount of weight our ship can carry given the average draft of the ship model. It is calculated as follows:

$Volume\ Displaced = 17413.221\ m^3$

$Density\ of\ Sea\ Water = 1025 \frac{kg}{m^3}$

$$Weight\ Displacement = 17413.221 * 1025$$
$$= 17848551.53\ kg$$

Afterwards create the hull surface using ‘MAXSURF MODELER’ software and find the KG and KB for complex curvature of your modelled ship. KG and KB can be found for both transverse and longitudinal direction but as mentioned before the critical side is transverse (11) (9).

$KG = 6.58\ m$

$KB = 3.207\ m$

BM (Metacentric Radius) and GM (Metacentric Height) are calculated using the formulas given below. Both are paramount values because they determine the initial stability. If the GM is greater than 0, the ship will not sink and vice versa.

$$BM = \frac{I}{\nabla}$$

$$BM = \frac{162238.98}{17413.221} = 9.32\ m$$

$$GM = KB + BM - KG$$

$$GM = 3.207 + 9.32 - 6.58 = 5.94\ m$$

Finally, the static stability curves are found by defining the weights and their Center of Mass. The curves are found using the 'MAXSURF STABILITY' software. It rotates the ship to large degrees and find the righting moment arm or GZ. If GZ is positive, the ship has the capacity to return to its upright position otherwise it will capsize (11) (8).

SECTION 4 | RESULTS & DISCUSSION

The results for the 'Design and Development' of mobile harbour include the hydrostatic properties of the modelled ship, its stability graphs and various other properties that depicts its stability in dynamic conditions. Most of the results are in the form of graphs, showing various properties as one or more properties are changed such as cross-sectional area, center of floatation, righting arm, displacement weight and center of buoyancy etc.

4.1 | PRELIMINARY SHIP DESIGN

Deadweight to displacement ratio of most of the cargo ships lies in range 0.65-0.8. Thus, a value of 0.7 was assumed. Since Froude number of 0.24 is considered to be safe Fn 0.24 was chosen. Deadweight, which is the variable weight of the ship was estimated to be 15,000,000 kg. The density of seas was assumed to be 1023 kg/m ^{3}. Based on these values all the other important values of preliminary design were calculated. The table below summarizes all the values of preliminary design i.e length, breadth draught, speed and all ship coefficients. It is interesting to note that L/B ratio of our ship is 5.62 while for most ships its range is 5.7- 7.8. The B/T ratio of most of the ships lies in the range 2.2-2.6 and B/T value of our ship is 2.49. For most ship the value of block coefficient ranges from 0.56-65 and the value of block coefficient of our ship is 0.629. Similarly, midship coefficients vary from 0.97-9.995; the midship coefficient of our ship is 0.978. As all criteria of preliminary design are within range our results are appropriate.

Table 1: Preliminary Design

Capacity (TEU)	
Deadweight (t)	15000
DWT/∇	0.7
Mass Displacemen (t)	21428.57
Displacment m3	20946.79514
Speed (Kn)	25
L (m)	137.825
B (m)	24.53
T (m)	9.84
Cb	0.62928

Cm	0.9783424
Cwl	0.752853258
Cp	0.643210393
S (m2)	4434.373729
Rtotal (kN)	- - -
Power (kW)	24108.8

4.2 | Resistance:

The density and viscosity of sea water were assumed to be 1023 kg/m ^{3} and 1.19x10^{-6} respectively. Based on the result of preliminary ship design and the assumed value of sea constants, different resistances were calculated. Frictional resistance was calculated as 514.98 kN while the value of wave resistance was roughly one fifth that of frictional resistance i.e. 100.25 kN. The appropriateness of wave resistance value can be realized from the fact that Froude number is greater than 18 hence waves were supposed to play a major role in total resistance [1]. Model ship correlation resistance played an equally important part in the total resistance with the value of 130.59 kN. Since other resistances did not add much to the total resistance they were neglected. The total resistance of the ship turned out to be 745.84 kN. Based on the total resistance value of ship and different efficiency values of thrust system, the total power required was calculated as 27.340 kW. The difference in the power calculated using resistance method and the one using admiralty constant is only 13.4 %. The difference is due to the fact that admiralty formula is an estimation formula which only takes speed and displacement into account. Based on power required by the ship; appropriate diameter of propeller was chosen. Results are summarized below with all values calculated.

Table 2: Inputs of Resistance Prediction

B (m)	26.4	**T/B**	0.2272
T (m)	6	**B/L**	0.1689
L (m)	156.3	**L/B**	5.92
A_{bt} (m^2)	20	**T_f (m)**	10
i_e (deg)	12.08	**h_b (m)**	4
Cm	0.97834	**A_t (m^2)**	16
Cwl	0.875	**L/T**	26.05
Cp	0.827	**V 0.333/L (m^2)**	0.126395
Cb	0.783	**L^3/V**	494.7525
Fn	0.24	**Density (m^3)**	1023
V (m^3)	17413	**Velocity (m/s)**	12.86
S (m^2)	4379	**Viscosity (Nsm^{-2})**	1.19E-06

Table 3: Results of Resistance Approximation

Re	2215569559	**c_1**	1.397787
C_f	0.00139002	**c_2**	0.759495
$1+k_1$	0.18663524	**c_3**	0.021191
C_{pv}	0.00025943	**c_5**	0.959184
R_{pv}	96115.0675	**c_7**	0.156098
C_A	0.000352	**c_{15}**	-1.69385
m_1	-2.06261	**c_{16}**	1.380719
m_2	-0.10157	**c_4**	0.04
R_f (N)	514988.852	**R_{total} (N)**	745840.7
R_W (N)	100254.1	**P_e (kW)**	9323
R_A (N)	130597.8	**P_d (kW)**	27340.201

4.3 | Encounter Frequency:

Since the stability of the ship is affected by forward speed of the ship, It is important to calculate the encounter frequency of the ship. We know that ship can experience waves from many different angles; encounter frequency for two extreme cases was calculate that is Head waves with angle of 180^o and Following waves with angle of 0^o . Wavelength was taken equal to length of the ship. The height of the wave was varied as shown in H/L row. Wave frequency was calculated as 0.62798 and based on these different encounter frequencies were calculated which are summarized below. It is interesting to note that magnitude of frequency of following wave keeps increasing with speed, which make it subtler to parametric roll of a ship.

Table 4: Frequency of Encounter

SL. No	1	2	3	4	5
Wave length	156.3	156.3	156.3	156.3	156.3
Wave height	2.605	3.9075	7.815	-	-
H/L	1/60	1/40	1/20	-	-
Mean GM (m)	0.74365	0.78945	1.02255	-	-
Still water GM (m)					
Wave frequency	0.62798	0.62798	0.62798	0.62798	0.62798
Forward Speed	3	6	9	12	15
Encounter Frequency (head sea)	0.748579	0.869178092	0.989777138	1.110376184	1.23097523
α (head sea)	0.1149497	0.085263998	0.065751914	0.052244787	0.042509364
Encounter Frequency (following sea)	0.507381	0.386781908	0.266182862	0.145583816	0.02498477
α (following sea)	0.2502159	0.430577104	0.909123858	3.039184305	103.1887907

4.4 | Ince-Strutt diagram:

Though the coefficient of damping of ship varies with speed, it was assumed to be 0.2 for all cases. GM variations were plotted using MAXSURF. The results are shown below: The sinusoidal shape is due to the fact that wave itself forms crest-trough-crest or vice versa on ship.

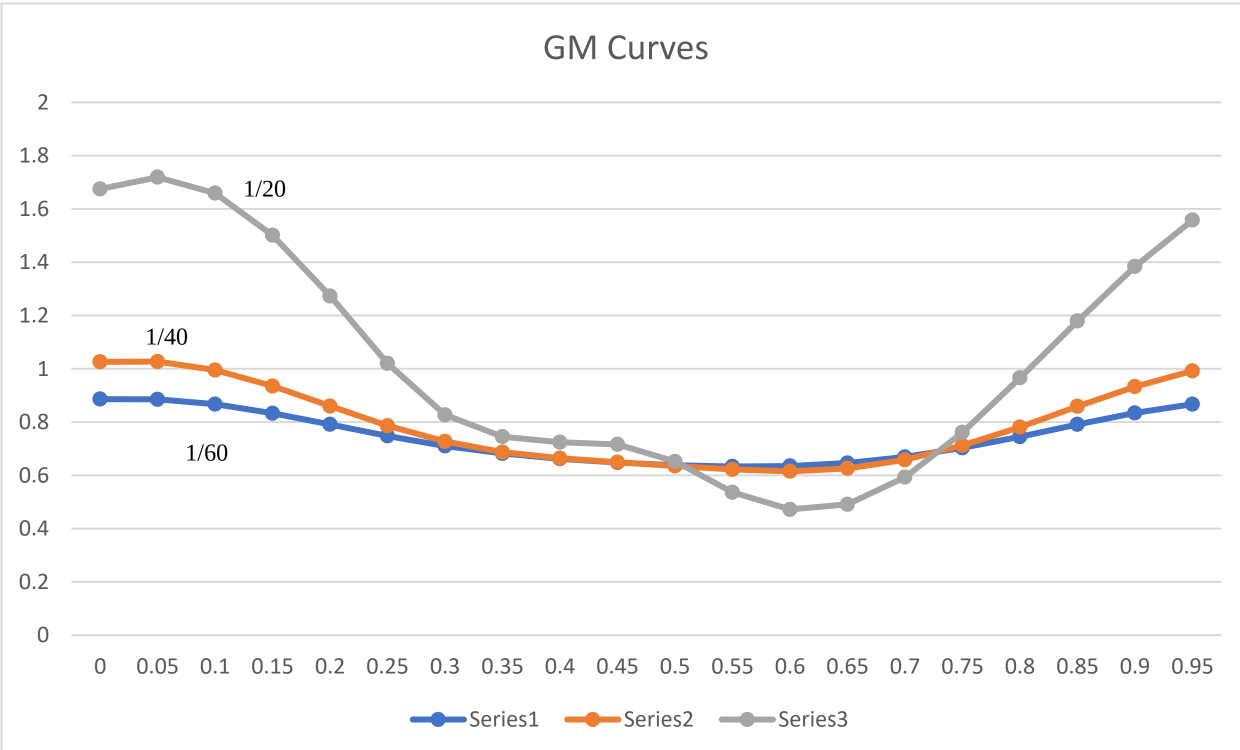


Figure 11:GM Curves of Various Wave Heights

These GM variations were used to calculate the coefficients for the Hills Matrix: Coefficients and their calculation is shown below:

Table 5: For Wave Height 2.605m

			n=1		n=2		n=3		n=4		n=5		n=6	
i	**t**	**GM**	**COS**	**SIN**	**COS**	**SIN**	**COS**	**SIN**	**COS**	**SIN**	**COS**	**SIN**	**COS**	**SIN**
1	**0**	**0.886**	0.886	0	0.886	0	0.886	0	0.886	0	0.886	0	0.886	0
2	**0.05**	**0.885**	0.837036	0.287395	0.698343	0.543638	0.483954	0.740955	0.217108	0.857956	-0.07327	0.881962	-0.35571	0.810368
3	**0.1**	**0.867**	0.684141	0.532581	0.212692	0.840507	-0.34847	0.793886	-0.76265	0.412385	-0.85511	-0.14307	-0.58687	-0.63817
4	**0.15**	**0.833**	0.455522	0.697418	-0.33481	0.762753	-0.82169	0.13679	-0.56386	-0.61315	0.205009	-0.80738	0.788074	-0.26987
5	**0.2**	**0.791**	0.194053	0.766829	-0.69579	0.376236	-0.53543	-0.58223	0.43309	-0.6619	0.747921	0.257479	-0.06613	0.788231
6	**0.25**	**0.748**	-0.06192	0.745432	-0.73775	-0.12343	0.184089	-0.72499	0.707263	0.243482	-0.3012	0.684676	-0.65739	-0.35685
7	**0.3**	**0.71**	-0.28536	0.650126	-0.4806	-0.52261	0.671708	-0.23002	-0.05936	0.707514	-0.62399	-0.33873	0.560962	-0.43523
8	**0.35**	**0.682**	-0.46205	0.501625	-0.05591	-0.6797	0.537816	0.419378	-0.67283	0.111446	0.373875	-0.57039	0.16623	0.661431
9	**0.4**	**0.662**	-0.58232	0.314877	0.36246	-0.55396	-0.05535	0.659682	-0.26509	-0.60661	0.521713	0.407504	-0.65275	-0.11031

-0.54166	0.535008	0.102421	-0.61508	0.398484	0.316288	-0.70082	0.2448	0.579609	-0.7653	0.004238
0.355678	0.347578	-0.62466	0.157783	0.508455	-0.58951	-0.05535	0.703632	-0.53827	-0.33147	0.86699
0.475901	-0.47032	-0.38762	0.532492	0.305877	-0.61346	-0.22612	0.722826	0.12735	-0.83141	0.003532
-0.4398	-0.4311	0.500441	0.345943	-0.56899	-0.26689	0.66564	0.180408	-0.78068	-0.06566	0.866993
-0.39722	0.392731	0.579204	-0.10581	-0.64391	-0.2157	0.589515	0.546728	-0.3785	-0.80784	0.002825
0.511977	0.502799	-0.25537	-0.62612	-0.05191	0.633272	0.382989	-0.50608	-0.69456	0.20723	0.866995
0.307754	-0.30438	-0.63091	-0.38925	0.210777	0.648823	0.516294	-0.12414	-0.72507	-0.69714	0.002119
-0.57026	-0.56071	-0.05138	0.501706	0.610646	0.163062	-0.47713	-0.73459	-0.31616	0.45777	0.866997
-0.20993	0.207676	0.530253	0.632777	0.47479	0.109321	-0.33539	-0.68266	-0.76651	-0.51124	0.001413
0.613052	0.603254	0.345718	-0.05309	-0.43805	-0.66001	-0.61784	-0.29833	0.195297	0.658933	0.866999
0.106411	-0.10528	-0.30154	-0.46741	-0.59173	-0.66675	-0.68138	-0.62341	-0.48539	-0.27019	0.000706
-0.6392	-0.62926	-0.55657	-0.42984	-0.25918	-0.05486	0.172996	0.407886	0.624549	0.789011	0.867
0.648	**0.638**	**0.633**	**0.635**	**0.646**	**0.669**	**0.703**	**0.745**	**0.791**	**0.834**	**0.867**
0.45	**0.5**	**0.55**	**0.6**	**0.65**	**0.7**	**0.75**	**0.8**	**0.85**	**0.9**	**0.95**
10	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**

A1	0.263246
B1	0.055178
A2	0.143962
B2	0.012631
A3	0.120028
B3	0.00381
A4	0.1198
B4	0.001767

Table 6:For wave height 3.9075 m

			n=1		n=2		n=3		n=4		n=5		n=6	
i	**t**	**GM**	**COS**	**SIN**	**COS**	**SIN**	**COS**	**SIN**	**COS**	**SIN**	**COS**	**SIN**	**COS**	**SIN**
1	**0**	1.026	1.026	0	1.026	0	1.026	0	1.026	0	1.026	0	1.026	0
2	**0.05**	1.027	0.971341	0.333508	0.810393	0.630866	0.561605	0.859842	0.251943	0.995617	-0.08503	1.023474	-0.41278	0.940393
3	**0.1**	0.995	0.785145	0.611209	0.244093	0.964595	-0.39992	0.911092	-0.87524	0.473267	-0.98136	-0.16419	-0.67352	-0.73239
4	**0.15**	0.935	0.5113	0.782816	-0.37581	0.856151	-0.92231	0.15354	-0.6329	-0.68823	0.230112	-0.90624	0.884573	-0.30291
5	**0.2**	0.86	0.210981	0.83372	-0.75649	0.409055	-0.58214	-0.63302	0.470869	-0.71964	0.813163	0.279939	-0.0719	0.856989
6	**0.25**	0.786	-0.06507	0.783301	-0.77522	-0.1297	0.193442	-0.76182	0.743193	0.255851	-0.3165	0.719459	-0.69078	-0.37498
7	**0.3**	0.727	-0.2922	0.665692	-0.49211	-0.53512	0.687791	-0.23553	-0.06078	0.724455	-0.63893	-0.34684	0.574394	-0.44565
8	**0.35**	0.687	-0.46544	0.505303	-0.05632	-0.68469	0.541759	0.422452	-0.67777	0.112263	0.376616	-0.57457	0.167449	0.666281
9	**0.4**	0.664	-0.58407	0.315829	0.363555	-0.55563	-0.05551	0.661675	-0.26589	-0.60844	0.523289	0.408735	-0.65472	-0.11064

-0.5425	0.532492	0.100641	-0.59571	0.386147	0.311087	-0.70979	0.256629	0.629436	-0.85614	0.004849
0.356226	0.345943	-0.6138	0.152813	0.492713	-0.57982	-0.05606	0.737633	-0.58454	-0.37082	0.991988
0.476636	-0.46811	-0.38088	0.515721	0.296407	-0.60337	-0.22902	0.757755	0.138298	-0.9301	0.004041
-0.44048	-0.42907	0.491745	0.335047	-0.55138	-0.26251	0.674162	0.189126	-0.84779	-0.07346	0.991992
-0.39783	0.390884	0.569139	-0.10247	-0.62398	-0.21216	0.597062	0.573147	-0.41104	-0.90374	0.003233
0.512767	0.500435	-0.25093	-0.6064	-0.0503	0.622859	0.387892	-0.53053	-0.75427	0.231829	0.991995
0.308229	-0.30294	-0.61995	-0.37699	0.204252	0.638155	0.522904	-0.13013	-0.7874	-0.77989	0.002425
-0.57114	-0.55808	-0.05049	0.485904	0.591741	0.16038	-0.48323	-0.77008	-0.34334	0.51211	0.991997
-0.21026	0.206699	0.521038	0.612847	0.46009	0.107524	-0.33968	-0.71565	-0.83241	-0.57192	0.001616
0.613998	0.600417	0.33971	-0.05142	-0.42449	-0.64916	-0.62575	-0.31274	0.212086	0.737152	0.991999
0.106575	-0.10479	-0.2963	-0.45268	-0.57341	-0.65579	-0.6901	-0.65353	-0.52711	-0.30226	0.000808
-0.64019	-0.6263	-0.5469	-0.41631	-0.25116	-0.05396	0.17521	0.427596	0.67824	0.882671	0.992
0.649	0.635	0.622	0.615	0.626	0.658	0.712	0.781	0.859	0.933	0.992
0.45	**0.5**	**0.55**	**0.6**	**0.65**	**0.7**	**0.75**	**0.8**	**0.85**	**0.9**	**0.95**
10	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**

B4	0.131074
A4	0.007205
B3	0.12876
A3	0.024754
B2	0.179859
A2	0.086488
B1	0.344405
A1	2.000000

Table 7: For wave height 7.815 m

			n=1		n=2		n=3		n=4		n=5		n=6	
i	**t**	**GM**	**COS**	**SIN**	**COS**	**SIN**	**COS**	**SIN**	**COS**	**SIN**	**COS**	**SIN**	**COS**	**SIN**
1	**0**	1.675	1.675	0	1.675	0	1.675	0	1.675	0	1.675	0	1.675	0
2	**0.05**	1.719	1.625837	0.558228	1.356442	1.055948	0.940019	1.43921	0.421704	1.666471	-0.14232	1.713098	-0.69092	1.574037
3	**0.1**	1.659	1.3091	1.019091	0.406985	1.608305	-0.6668	1.519096	-1.45932	0.789096	-1.63626	-0.27376	-1.12298	-1.22114
4	**0.15**	1.501	0.820814	1.256692	-0.6033	1.374421	-1.48062	0.246485	-1.01603	-1.10484	0.36941	-1.45483	1.420047	-0.48628
5	**0.2**	1.273	0.3123	1.2341	-1.11978	0.605497	-0.8617	-0.93702	0.696996	-1.06523	1.20367	0.414375	-0.10643	1.268543
6	**0.25**	1.02	-0.08444	1.016498	-1.00602	-0.16832	0.251031	-0.98863	0.964449	0.332021	-0.41073	0.933649	-0.89644	-0.48662
7	**0.3**	0.827	-0.33239	0.757259	-0.5598	-0.60873	0.782398	-0.26792	-0.06914	0.824105	-0.72682	-0.39454	0.653403	-0.50695
8	**0.35**	0.745	-0.50473	0.547963	-0.06108	-0.74249	0.587497	0.458118	-0.73499	0.121741	0.408412	-0.62308	0.181586	0.722531
9	**0.4**	0.724	-0.63685	0.344367	0.396406	-0.60584	-0.06053	0.721465	-0.28992	-0.66342	0.570574	0.445669	-0.71388	-0.12064

-0.5985	0.546748	0.086726	-0.4572	0.302873	0.280357	-0.75864	0.317418	0.863918	-1.26999	0.007616
0.393002	0.355205	-0.52894	0.117281	0.386457	-0.52254	-0.05992	0.912361	-0.8023	-0.55007	1.557981
0.525842	-0.48064	-0.32822	0.395805	0.232486	-0.54377	-0.24478	0.937249	0.189817	-1.3797	0.006346
-0.48595	-0.44056	0.423755	0.257142	-0.43247	-0.23657	0.720558	0.233925	-1.16362	-0.10897	1.557987
-0.4389	0.401349	0.490447	-0.07865	-0.48941	-0.1912	0.638152	0.708911	-0.56416	-1.34059	0.005077
0.565703	0.513832	-0.21623	-0.4654	-0.03946	0.56133	0.414587	-0.6562	-1.03526	0.343892	1.557992
0.340049	-0.31106	-0.53423	-0.28933	0.160204	0.575116	0.55889	-0.16096	-1.08073	-1.15688	0.003808
-0.6301	-0.57302	-0.04351	0.372921	0.464129	0.144537	-0.51649	-0.9525	-0.47124	0.759657	1.557995
-0.23196	0.212233	0.448998	0.470348	0.360869	0.096902	-0.36306	-0.88517	-1.1425	-0.84838	0.002539
0.677384	0.616491	0.292741	-0.03946	-0.33295	-0.58503	-0.66881	-0.38682	0.291093	1.093481	1.557998
0.117577	-0.10759	-0.25533	-0.34743	-0.44975	-0.591	-0.73759	-0.80834	-0.72348	-0.44837	0.001269
-0.70628	-0.64306	-0.47128	-0.31951	-0.19699	-0.04863	0.187269	0.528883	0.930902	1.309343	1.558
0.716	0.652	0.536	0.472	0.491	0.593	0.761	0.966	1.179	1.384	1.558
0.45	**0.5**	**0.55**	**0.6**	**0.65**	**0.7**	**0.75**	**0.8**	**0.85**	**0.9**	**0.95**
10	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**

			A1	B1	A2	B2	A3	B3	A4	B4				
			0.617406	0.233158	0.29348	0.06255	0.125049	0.028916	0.169531	0.004005				

Finally, the Mathieu matrix and Hill matrix were solved for 2π and 4π solution. In both the cases the damping coefficient was assumed to be 0.2.

2π:

$$\begin{bmatrix} \alpha & 0.098\gamma & 0.0205\gamma & 0.0535\gamma \\ 0.196\gamma & \alpha - 1 & 0.0045\gamma + 0.2 & 0.1425\gamma \\ 0.041\gamma & 0.0045\gamma - 0.2 & \alpha - 1 - 0.0535\gamma & -0.019\gamma \\ 0.107\gamma & 0.1425\gamma & -0.019\gamma & \alpha - 4 + 0.0445\gamma \end{bmatrix}$$

4 π:

$$\begin{bmatrix} \alpha - \frac{1}{4} & 0.0205\gamma + 0.1 & 0.152\gamma & 0.025\gamma \\ 0.041\gamma - 0.1 & \alpha - 0.25 - 0.098\gamma & -0.016\gamma & -0.0445\gamma \\ 0.152\gamma & -0.016\gamma & \alpha - 2.25 + 0.0445\gamma & 0.0015\gamma + 0.3 \\ 0.025\gamma & 0.0445\gamma & 0.0015\gamma - 0.3 & \alpha - 2.25 - 0.445\gamma \end{bmatrix}$$

2 π:

$$\begin{bmatrix} \alpha & 0.136\gamma & 0.342\gamma & 0.071\gamma \\ 0.272\gamma & \alpha - 1 & 0.00975\gamma + 0.2 & 0.187\gamma \\ 0.0683\gamma & 0.00975\gamma - 0.2 & \alpha - 1 - 0.071\gamma & -0.0313\gamma \\ 0.142\gamma & 0.187\gamma & -0.0313\gamma & \alpha - 4 + 0.0515\gamma \end{bmatrix}$$

4 π:

$$\begin{bmatrix} \alpha - 0.25 + 0.136\gamma & 0.0342\gamma + 0.1 & 0.207\gamma & 0.0439\gamma \\ 0.0683\gamma - 0.1 & \alpha - 0.25 - 0.135\gamma & -0.0244\gamma & -0.065\gamma \\ 0.207\gamma & -0.0244\gamma & \alpha - 2.25 + 0.051\gamma & 0.00285\gamma + 0.3 \\ 0.0439\gamma & 0.065\gamma & 0.00285\gamma - 0.3 & \alpha - 2.25 - 0.051\gamma \end{bmatrix}$$

These Matrices were used to plot Ince Strutt diagrams. Results are shown below for time series vs. roll motion of ship and Hill chart representing stable and unstable region specifically of our own ship

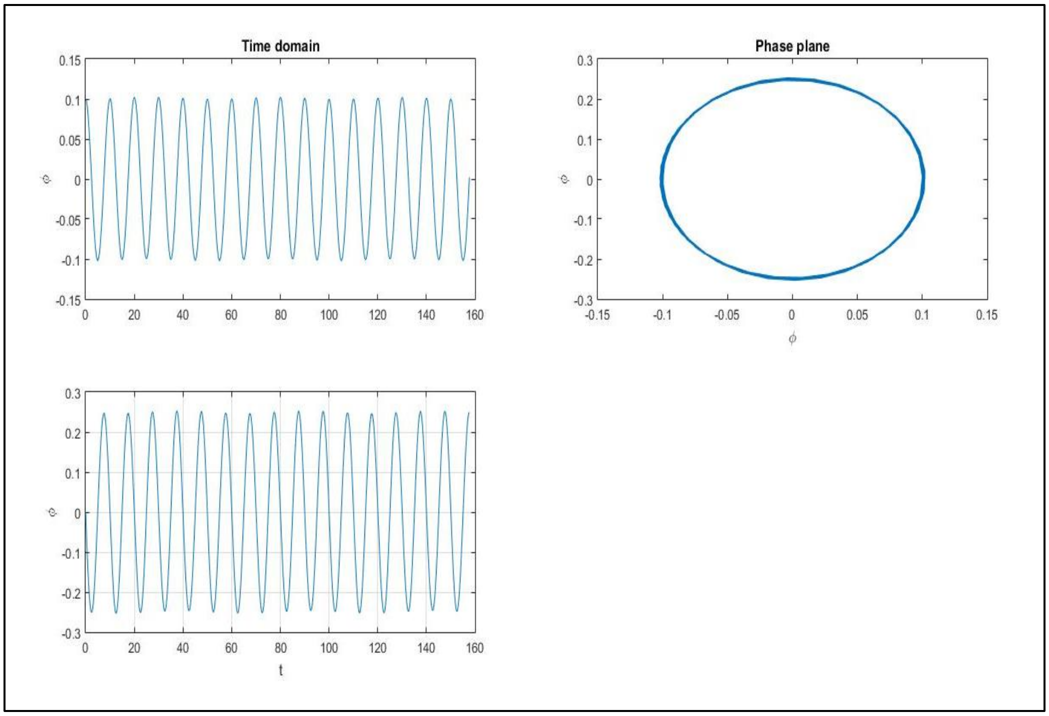


Figure 12: Time Series of Motion with V=3 m/s

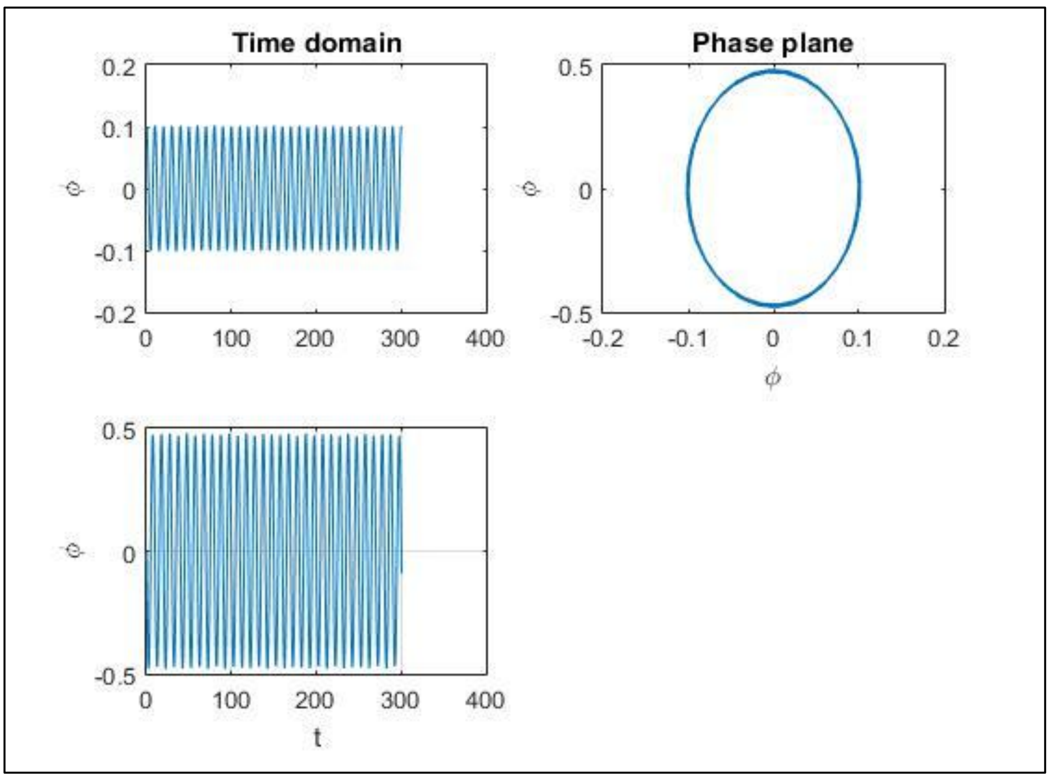


Figure 13: Time Series of Motion with V=9 m/s

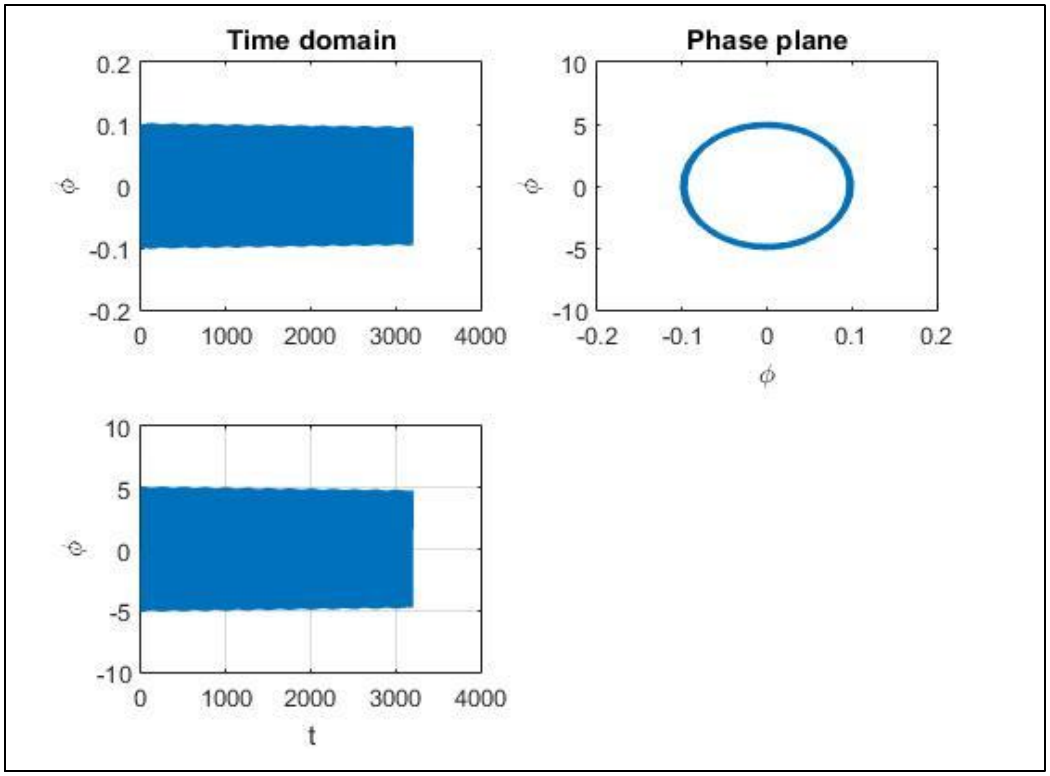


Figure 14: Time Series of Motion with V=15 m/s

Time series vs roll motion of ship are plotted for simplified Mathieu equation i.e. without damping for various speeds. Plots in Figure 16,17 & 18 are specifically shown for speed 3 m/s, 9m/s and 15 m/s. Though the magnitude of roll changes, all of these plots predict that no parametric roll occurs at these speeds. However, a special case is discussed below in which encounter frequency equals twice the natural frequency. The Figure 19 clearly shows that parametric roll occurs as is mentioned in (8) (10). Therefore, the simplified Mathieu equation can be considered accurate for some very basic rules. The validity for different speeds at different wave heights require the use of Hill charts which are discussed below.

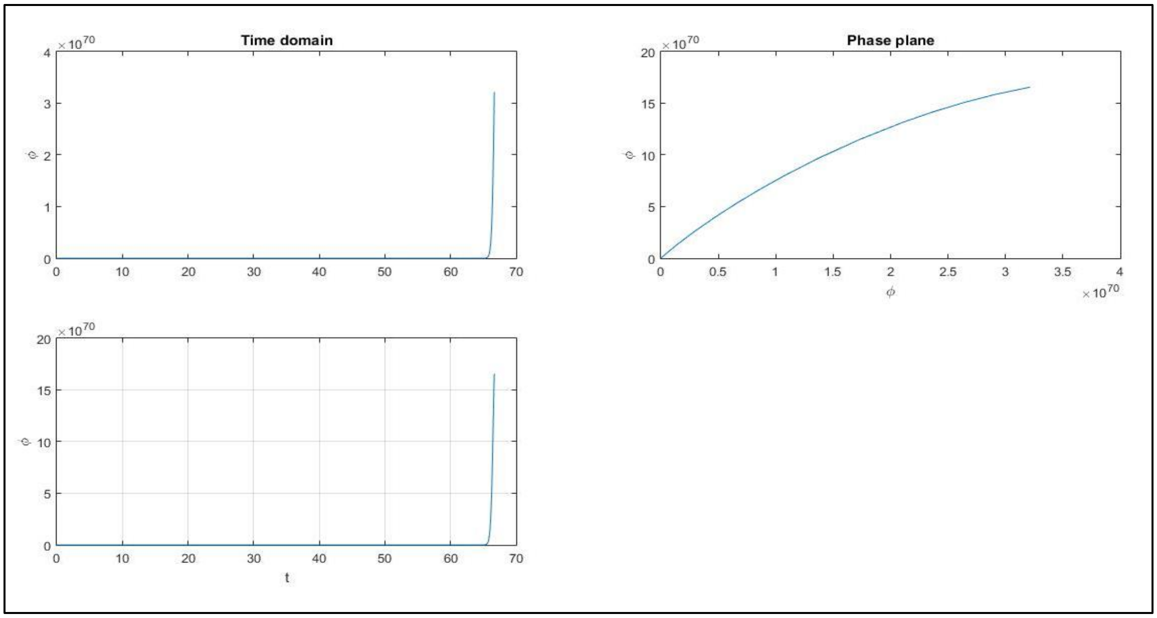


Figure 16: Time series of motion when natural frequency

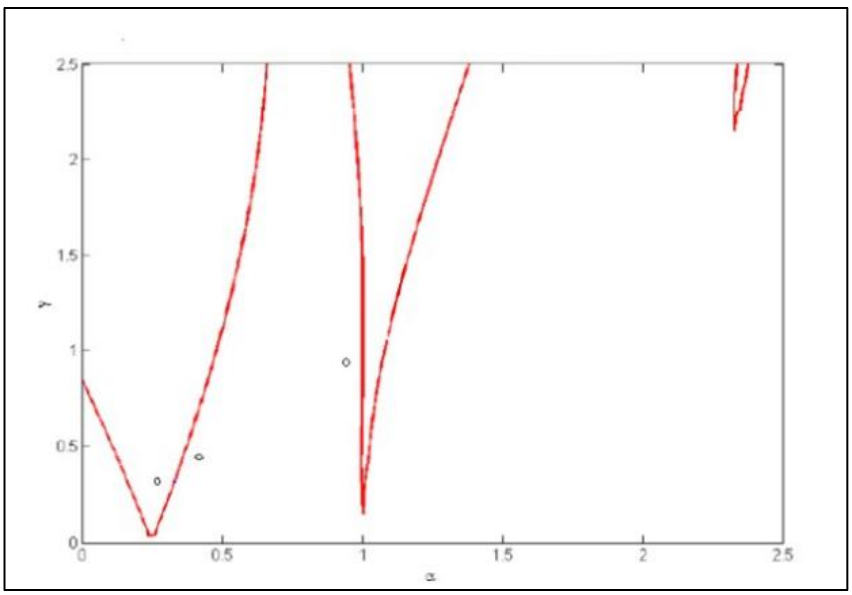


Figure 15: Hill Chart for H=2.62 m

Figure 20 represents hill chart for wave height 2.62 m. From the diagram it can be deduced that the ship will experience parametric roll at velocity of 3 m/s therefore the speed of 3m/s is likely to be avoided. Moreover, velocity of 6 m/s and 9 m/s are considered to be safe.

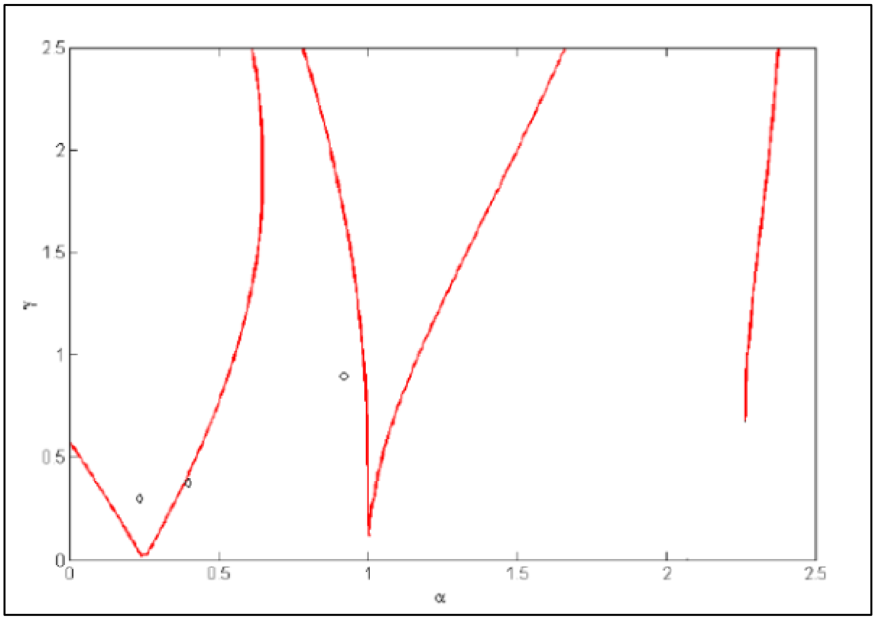


Figure 17: Hill Chart for H=4 m

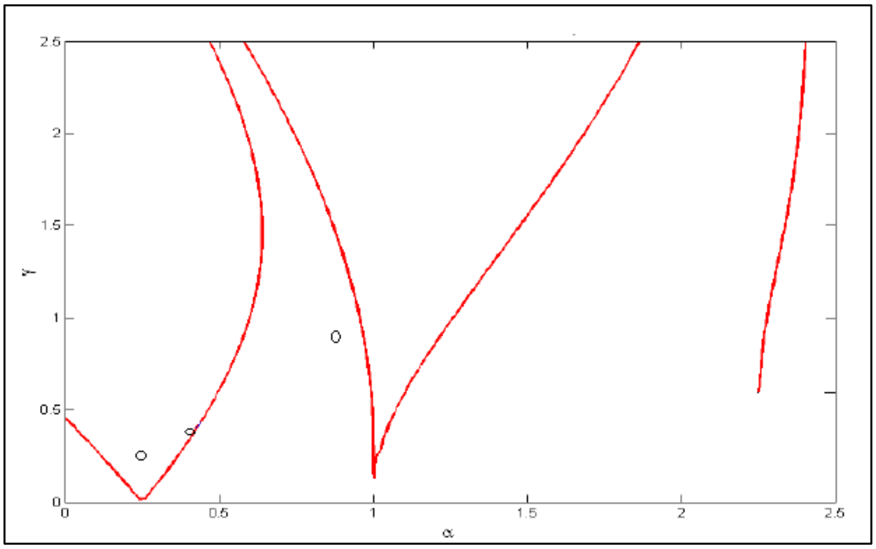


Figure 18: Hill chart for H=7 m

Below is Figure 21 which is for wave height 4 m, predicts that a ship can sink at 3 m/s. Moreover, speed of 6 m/s can prove too dangerous as it’s at the verge of parametric roll. In Figure 22 it can be clearly seen that a ship can experience parametric roll at two different velocities that are 3m/s and 6 m/s. As expected with an increase in wave height the unstable area increases resulting in a change of stability for different forward speed. As a result, more, parametric roll is observed in such cases.

4.5 | STABILITY OF SHIP

The first graph is about the cross-sectional area of the modelled ship in the longitudinal direction. In other words, it can also be called as the cross-sectional area of the stations if the station thickness supposedly reaches zero. As depicted in the graph, the cross-sectional area changes smoothly from the stern to the front and remains close to its maximum value for the major part of its length. Secondly, this curve is also important to analyze the curvature of the ship. It means there are no sharp or dramatic change in cross-sectional areas of the ship. On the other hand, if there are sharp deviations, there are sudden changes in the curvature of the ship as well. This is not appropriate for the general functioning of the modelled ship. This graph is known as the 'Curve of Areas'.

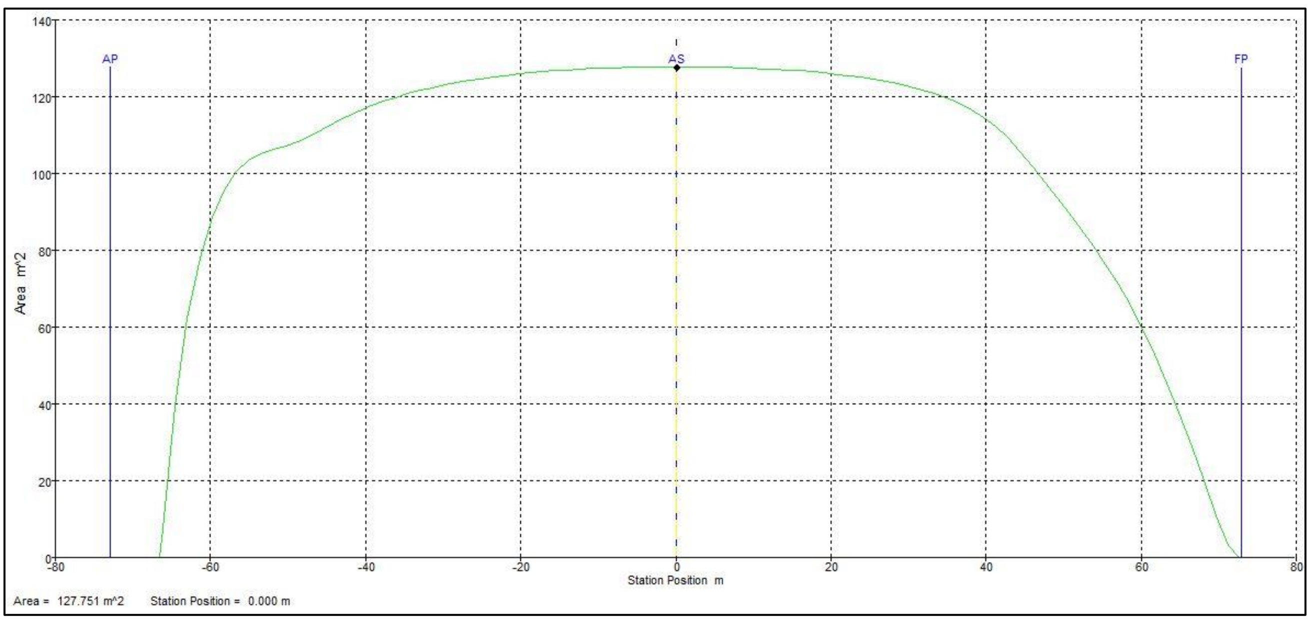


Figure 19: Curve of Areas

The second graph shows the change in hydrostatic properties at various draft lengths and displacement weight. It tells us all the basic yet mandatory properties of the modelled ship if it operates at different drafts and under varying displacement weights. It tells the following properties:

1. Displacement
2. Draft
3. Sectional Areas
4. Waterplane Areas
5. LCB
6. LCF
7. KML
8. KMt
9. KB
10. TPc

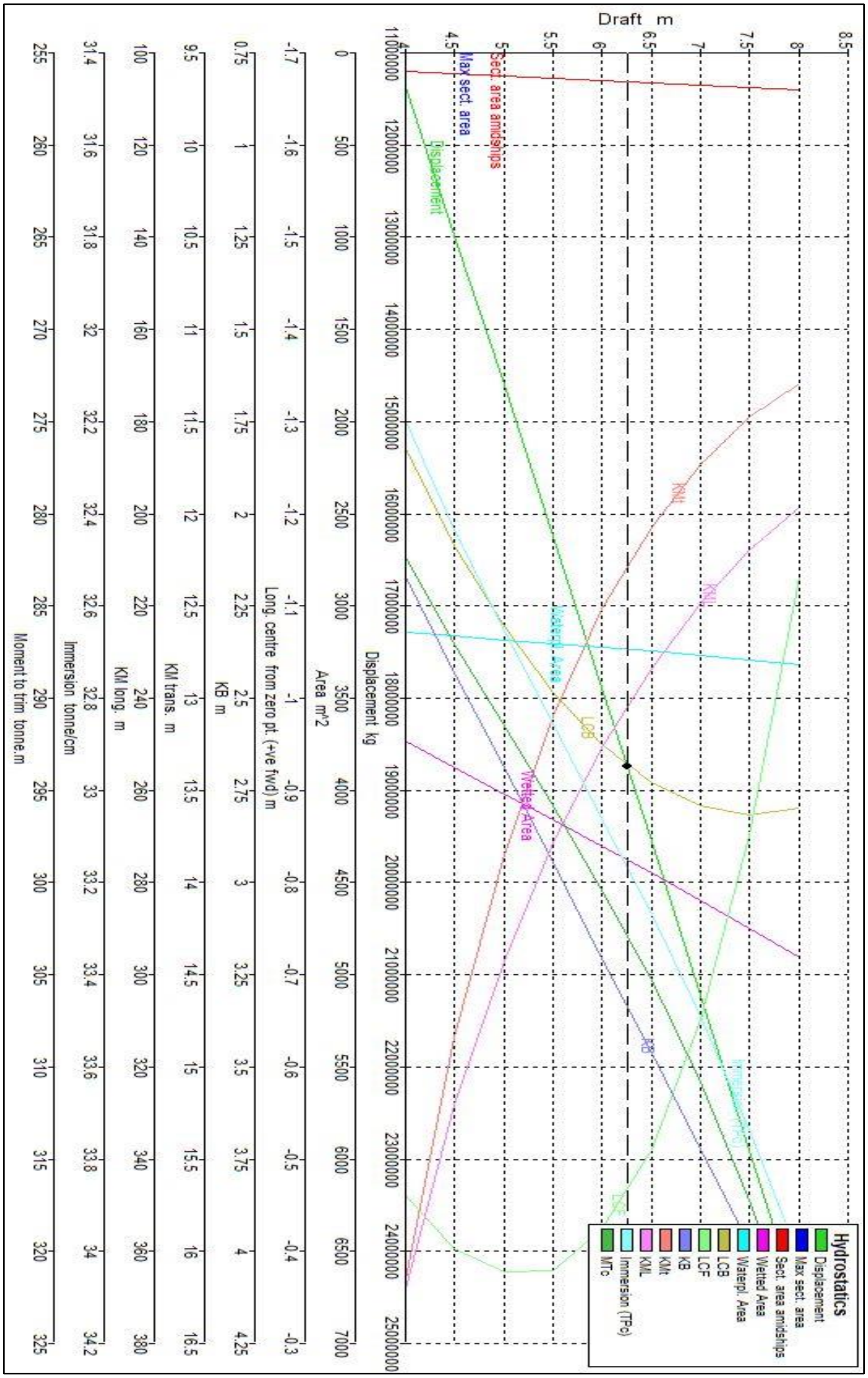


Figure 20: Hydrostatic Properties

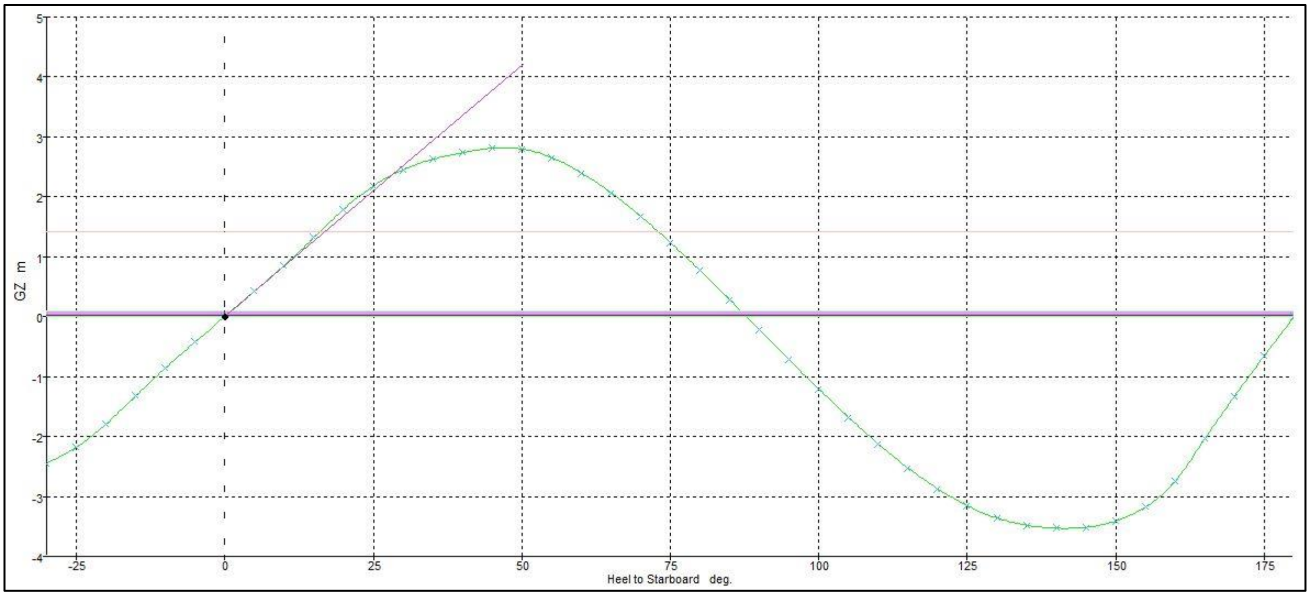


Figure 21: GZ Curve

The above graph is the most important graph in determining the stability of the modelled ship at different angles of heel. It is called the "GZ Curve'. This curve forms under the following conditions:

Table 8: Load Case

Item Name	Quantity	Unit Mass (kg)	Total Mass (kg)	Longitudina l Arm (m)	Transverse Arm (m)	Vertical Arm (m)
Hull	1	5000000	5000000	0	0	0.54
Cargo	1	10000000	10000000	0	0	4
Total Load case			15000000	0	0	2.847
FS correction						0
VCG fluid						2.847

The graph is formed under the total load of 15000000kg. The vertical center of gravity is also indicated from the zero position of the modelled ship. The graph shows that the ship is in upright state at zero angle of heel in the starboard direction. As the angle of heel increases the righting arm increases (GZ length) increases as well. It reaches its maximum value of 2.8m at around 50 degrees of heel angle and then it starts to decrease. The positive righting arm means that the modelled ship has the capability to return to its upright state if the external force is removed. Around 87 degrees of heel angle the righting arm remains negative which means after this heel angle the ship will capsize. This point is known as

"Point of Vanishing Stability". At 30 degrees of heel angle the righting arm is greater than 1 which is appropriate for container ship designs. The total range for which the GZ is positive is called the "Range of Stability". Moreover, the point at which the curve changes its shape is called the "Point of Deckage Immersion".

The other graph is the "Dynamic Stability" graph which shows the stability under moving conditions. The results are quite raw since better approach is explained later in this section. But in brevity, this graph is produced by finding the area under the "GZ Curve". If "GZ Curve" is adequate, this graph shows for what range of heel angles is the ship dynamically stable. The y-axis of the graph is in degrees*m and the x-axis is in degrees.

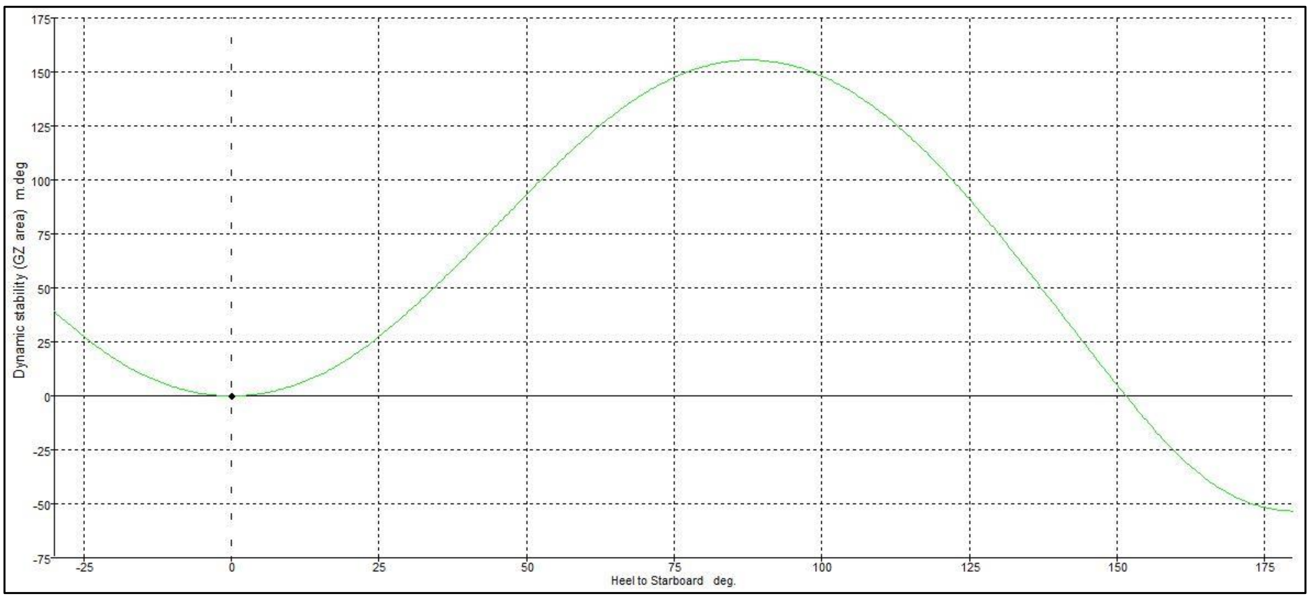


Figure 22: Dynamic Stability

SECTION 5 | PROGRAMMING OF LINEAR ACTUATOR

```
//Gyro - Arduino UNO R3
//VCC  -  5V
//GND  -  GND
//SDA  -  A4
//SCL  -  A5
//INT - port-2

#include <Wire.h>
#include <Stepper.h>

//Declaring some global variables

const int STEPS_PER_REV = 200;
Stepper stepper_NEMA17(STEPS_PER_REV, 8, 9, 10, 11);
int button1 = 6;
int buttonState1 = 0;
int button2 = 7;
int buttonState2 = 0;

int gyro_x, gyro_y, gyro_z;
long gyro_x_cal, gyro_y_cal, gyro_z_cal;
boolean set_gyro_angles;

long acc_x, acc_y, acc_z, acc_total_vector;
float angle_roll_acc, angle_pitch_acc;

float angle_pitch, angle_roll;
int angle_pitch_buffer, angle_roll_buffer;
float angle_pitch_output, angle_roll_output;
```

```
long loop_timer;
int temp;

void setup() {
  pinMode(button1, INPUT);
  pinMode(button2, INPUT);
  Wire.begin();
//Start I2C as master
  setup_mpu_6050_registers();
//Setup the registers of the MPU-6050
  for (int cal_int = 0; cal_int < 1000 ; cal_int ++){
//Read the raw acc and gyro data from the MPU-6050 for 1000 times
    read_mpu_6050_data();
    gyro_x_cal += gyro_x;
//Add the gyro x offset to the gyro_x_cal variable
    gyro_y_cal += gyro_y;
//Add the gyro y offset to the gyro_y_cal variable
    gyro_z_cal += gyro_z;
//Add the gyro z offset to the gyro_z_cal variable
    delay(3);
//Delay 3us to have 250Hz for-loop
  }

  // divide by 1000 to get avarage offset
  gyro_x_cal /= 1000;
  gyro_y_cal /= 1000;
  gyro_z_cal /= 1000;
  Serial.begin(115200);
  loop_timer = micros();
//Reset the loop timer

  //checking
```

```
  if (digitalRead(button1) == LOW)
  {
    Serial.println("Button 1 is LOW");
  }
   if (digitalRead(button2) == LOW)
  {
    Serial.println("Button 2 is LOW");
  }

Serial.print(gyro_x_cal);Serial.print("\t");Serial.print(gyro_y_c
al);Serial.print("\t");Serial.println(gyro_x_cal);
  //stepper_NEMA17.setSpeed(150);
}


void loop(){
  stepper_NEMA17.setSpeed(100);
  buttonState1 = digitalRead(button1);
  buttonState2 = digitalRead(button2);
  //Serial.print(buttonState1);Serial.print("\t");
  //Serial.println(buttonState2);
  read_mpu_6050_data();
  dataprocessing();
  while(micros() - loop_timer < 4000);
//Wait until the loop_timer reaches 4000us (250Hz) before
starting the next loop
  loop_timer = micros();//Reset the loop timer
}


void setup_mpu_6050_registers(){
  //Activate the MPU-6050
  Wire.beginTransmission(0x68);
//Start communicating with the MPU-6050
```

```
  Wire.write(0x6B);
//Send the requested starting register
  Wire.write(0x00);
//Set the requested starting register
  Wire.endTransmission();
  //Configure the accelerometer (+/-8g)
  Wire.beginTransmission(0x68);
//Start communicating with the MPU-6050
  Wire.write(0x1C);
//Send the requested starting register
  Wire.write(0x10);
//Set the requested starting register
  Wire.endTransmission();
  //Configure the gyro (500dps full scale)
  Wire.beginTransmission(0x68);
//Start communicating with the MPU-6050
  Wire.write(0x1B);
//Send the requested starting register
  Wire.write(0x08);
//Set the requested starting register
  Wire.endTransmission();
}



void read_mpu_6050_data(){
//Subroutine for reading the raw gyro and accelerometer data
  Wire.beginTransmission(0x68);
//Start communicating with the MPU-6050
  Wire.write(0x3B);
//Send the requested starting register
  Wire.endTransmission();
//End the transmission
  Wire.requestFrom(0x68,14);
//Request 14 bytes from the MPU-6050
```

```
  while(Wire.available() < 14);
//Wait until all the bytes are received
  acc_x = Wire.read()<<8|Wire.read();
  acc_y = Wire.read()<<8|Wire.read();
  acc_z = Wire.read()<<8|Wire.read();
  temp = Wire.read()<<8|Wire.read();
  gyro_x = Wire.read()<<8|Wire.read();
  gyro_y = Wire.read()<<8|Wire.read();
  gyro_z = Wire.read()<<8|Wire.read();
}


void dataprocessing(){
  gyro_x -= gyro_x_cal;
  gyro_y -= gyro_y_cal;
  gyro_z -= gyro_z_cal;


  //Gyro angle calculations . Note 0.0000611 = 1 / (250Hz x 65.5)
  angle_pitch += gyro_x * 0.0000611;
//Calculate the traveled pitch angle and add this to the
angle_pitch variable
  angle_roll += gyro_y * 0.0000611;
//Calculate the traveled roll angle and add this to the
angle_roll variable
  //0.000001066 = 0.0000611 * (3.142(PI) / 180degr) The Arduino
sin function is in radians
  angle_pitch += angle_roll * sin(gyro_z * 0.000001066);
//If the IMU has yawed transfer the roll angle to the pitch angel
  angle_roll -= angle_pitch * sin(gyro_z * 0.000001066);
//If the IMU has yawed transfer the pitch angle to the roll angel


  //Accelerometer angle calculations
  acc_total_vector =
sqrt((acc_x*acc_x)+(acc_y*acc_y)+(acc_z*acc_z));  //Calculate the
total accelerometer vector
```

```
  //57.296 = 1 / (3.142 / 180) The Arduino asin function is in radians
  angle_pitch_acc = asin((float)acc_y/acc_total_vector)* 57.296;       //Calculate the pitch angle
  angle_roll_acc = asin((float)acc_x/acc_total_vector)* -57.296;       //Calculate the roll angle

  angle_pitch_acc -= 0.0;                                              //Accelerometer calibration value for pitch
  angle_roll_acc -= 0.0;                                               //Accelerometer calibration value for roll

  if(set_gyro_angles){                                                 //If the IMU is already started
    angle_pitch = angle_pitch * 0.9996 + angle_pitch_acc * 0.0004;     //Correct the drift of the gyro pitch angle with the accelerometer pitch angle
    angle_roll = angle_roll * 0.9996 + angle_roll_acc * 0.0004;        //Correct the drift of the gyro roll angle with the accelerometer roll angle
  }
  else{                                                                //At first start
    angle_pitch = angle_pitch_acc;                                     //Set the gyro pitch angle equal to the accelerometer pitch angle
    angle_roll = angle_roll_acc;                                       //Set the gyro roll angle equal to the accelerometer roll angle
    set_gyro_angles = true;                                            //Set the IMU started flag
  }

  //To dampen the pitch and roll angles a complementary filter is used
  angle_pitch_output = angle_pitch_output * 0.9 + angle_pitch * 0.1;   //Take 90% of the output pitch value and add 10% of the raw pitch value
```

```
  angle_roll_output = angle_roll_output * 0.9 + angle_roll * 0.1;
//Take 90% of the output roll value and add 10% of the raw roll
value

  //Serial.print("Angle = "); Serial.print(angle_pitch_output);
Serial.println("\t");

  //Serial.print(" | Angle  = ");
Serial.println(angle_roll_output);

  if (buttonState1 == LOW){

    Serial.println("Button2 is not pressed");


    if (angle_pitch_output >= 5.0 &&  angle_pitch_output <90.0)

    {

      stepper_NEMA17.step(+(STEPS_PER_REV/100));

    }

  }

  if (buttonState2 == LOW){

    Serial.println("Button1 is not pressed");

    if (angle_pitch_output >=-90.0 &&  angle_pitch_output < -5.0)

    {

      stepper_NEMA17.step(-(STEPS_PER_REV/100));

    }

  }

}
```

SECTION 6 | CONCLUSION

1) The modelled ship needs to be stable which means it should remain in an upright condition in most of the circumstances for which GM needs to be greater than 1. This is the case in our modelled ship.
2) GZ curve tells the stability of the ship under angles of heel. The modelled ship has the tendency to return to its upright state until 85 degrees of heel angle. This is the second criteria for checking the ship stability.
3) The single degree of roll equation of motion with time varying linear stiffness can be reduced to a Hill or Mathieu form.
4) The Hill's form is capable of representing the non-harmonically varying stiffness variation much better than Mathieu.
5) The effect of forward speed was to shift the parameters (α, γ) in the Ince-Strutt diagram.
6) Damping uplifts, the Ince-Strutt diagram.
7) Power required to propel the ship is related to the total resistance of the ship and the velocity at which the ship will sweep through water. More the velocity and the resistance, more the power required
8) Length, Breadth and Draught must be in proper ratio. If they are not it may cause high ship resistance and non-uniform stress regions in the ship. Also, breadth is directly dependent on GM which directly affects stability. The same is true for ship coefficients

SECTION 7 | RECOMMENDATIONS

During the research several different topics were brought into attention that could have been given further attention. Some of them are:

1) Parametric roll should be studied for different waves i.e. other than head and following waves. A wave can hit a ship from many different angles during its voyage. Thus, roll excitation should be studied for other wave angles as well.
2) Most appropriate conditions/parameter should be chosen to study ship stability and these can be chosen by designing a ship for a specific sea route undertaking all the extreme conditions.
3) Since damping coefficient varies with roll amplitude and velocity of ship, more precise results can be achieved if damping coefficient is determined using roll amplitude variations and velocity variations.
4) Irregular sea waves should be considered because they would result in instantaneous transfer functions and different GM variation. Also, the natural frequency of the vessel becomes a variable.

   We assumed constant volume displacement of ship nut that will also vary in irregular seaways.

SECTION 8 | REFERENCES

1. **Papanikolaou, Apostolos.** *Ship Design - Methodologies of Preliminary Design.*

2. *Designing Constraints in Evaluation of Ship Propulsion.* **Charchalis, Adam.**

3. *Main Dimensions Selection Methodology of the Container Vessel in the Preliminary Design.* **Charchalis, Adam, J. Krefft.**

4. **H. Schneekulth, V. Bertram.** *Ship Design for Efficiency and Economy.*

5. *An Approximate Power Prediction Method.* **J. Holtrop, G.G.J. Mennen.** 1982.

6. **Ventura, Manuel.** *Estimation Methods for Basic Ship Design.*

7. **PURSEY, H. J.** *Merchant Ship Stability.* s.l. : BROWN, SON & FERGUSON, LTD., NAUTICALPUBLISHERS, 1996.

8. **Adrian B. Biran, Rubén López-Pulido.** *Ship Hydrostatics and Stability.* s.l. : Butterworth-Heinemann Publications, 2014.

9. **Warrior, Dr. Hari V.** Ocean - Hydrstatics and Stability. [Online] NPTEL, 2014. https://onlinecourses.nptel.ac.

10. *Prediction of Parametric Roll of Ship in Regular and Irregular Sea.* **Moideen, Hisham.**

11. **Bentley.** MAXSURF. [Online] Bentley. [Cited: November 15, 2017.] https://www.bentley.com.