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# Cargo Securing Requirements and Environmental Conditions


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by

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EMship+ Advanced Design

# Master Thesis

# TABLE OF CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

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## ABSTRACT

Container shipping officially came into being in 1956 when an American businessman filed a patent for the first container ship. In less than 65 years, the container ships have revolutionized to such great extent that now they have become the work-horses of the globalized economy. With the increasing ship sizes, modernization of cargo transport and growing demand of safe and cost saving ocean freight shipping, the classification societies are continuously focusing to make the ships more safe and secure in order to ensure safety of containers, cargo and the crew.

Forces are exerted on ship's hull as a result of ship's movements in waves. These forces are transferred to the stowed containers in the form of accelerations. To determine these accelerations for different cases and various sizes of ships, DNV.GL has been engaged to revise the rules and standards accordingly. For the same purpose, two internal software programs, QUERROLL and StowLash are used by DNV.GL to analyze the forces being exerted on the containers and its consequences by calculating the accelerations.

A study is made for six ships of different sizes and cargo capacity and the accelerations are evaluated by the two software for different parts of the ship considering different metacentric heights, from low to high. The results are analyzed and comparisons are made to determine the accuracy of the software and feasibility of the formulae used in the codes. The impact on the output acceleration by reducing the ship's speed as an input parameter in both software was estimated and the results for a range of lower speeds were formulated and compared.

Observing the results and by doing comparisons, inaccuracy of the approximation formula used in QUERROLL was determined for higher metacentric heights and lower speeds. Inconsistency of the software regarding ship size was observed which displayed no valid calculation pattern for particularly smaller or larger ships. The comparison declared StowLash results to be no more on the conservative side since in most of the cases, QUERROLL formulated higher values of accelerations. The lower limit of speed as input parameter in StowLash was also determined for ultra large container vessels with a cargo capacity of around 20,000 TEU or more.

# 1. INTRODUCTION

With shipping being the backbone of international trade, the seismic change of containerization has made container vessels one of the most dynamic mode of hauling non bulk goods. In the recent era, the container ships carry around 90% of world's non bulk cargo.

With the modernization of transport and increasing market demands, the container vessels have become even bigger and this expansion is continuous, providing increased cargo storage capacity. In almost a decade, the container ship size has remarkably grown and the cargo capacity has doubled with an increase of more than 1200% as compared to 1968.

The safe and adequate stowage of the intermodal containers on a cargo vessel has a sheer importance for the safety of the cargo, the vessel and the crew members. For the purpose to secure the cargo, lashing system is used on the containers to make them rigid to the ship's structure. During the voyage, a container vessel undergoes different weather conditions varying from calm to rough. If the containers are not lashed and stowed in a proper manner with a valid plan, they might experience shifting which could result in the cargo damage, loss of containers or the crew might face a risk of injury. This loss of containers and crashing into the sea does not only pose financial threat but also can cause environmental pollution and floating of containers on sea surface can be dangerous for other vessels too.

Varying weather conditions are likely to exert multiple forces on the vessel. These forces mainly result from surging, swaying, yawing, rolling, pitching or heaving or a combination of these motions. These forces produce loads on the stowed containers in the form of vertical and horizontal accelerations.

Lateral accelerations poses the greatest threat on the stacks of the container as they tend to lift and compress either sides of the stack. To hold the stacks firmly in their location, lashing assemblies are used to avoid displacement of the stacks and shift of the containers.

## 1.1. Container Dimensions and Types

An intermodal container is a standardized cargo holding unit made up of steel and manufactured in various types and sizes depending upon the transportation and cargo requirements. Most widely used containers are 20 and 40 feet long and the common heights are 8 feet 6 inches and 9 feet 6 inches.

Container vessels with capacity of 10,000 TEU and above are already in operation and are termed as Ultra Large Container Vessel (ULCS). Currently, the recently launched ‘HMM Algeciras’ is the world’s largest container ship operating with container capacity of 24,000 TEU.

Figure 1.1. displays the arrangement of containers on a vessel. The container positioning is defined by a bay-row-tier coordinate system. The bay portrays the cross sections of the ship and is numbered from aft to stern. The row runs along the longitudinal length of the ship and is numbered from the middle of the ship’s breadth outwards with odd numbers on the starboard side and even numbers on the port side. The tier portrays the container layers and are numbered from top to bottom.

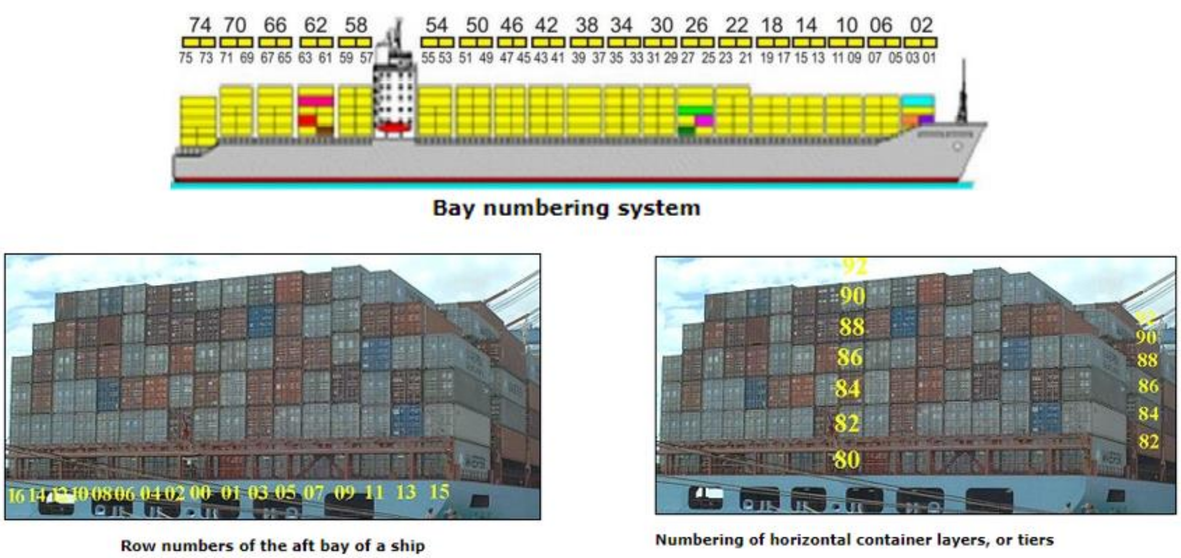



Figure 1.1. Container Stowage Plan. Available from
http://www.containerhandbuch.de/chb_e/stra/index.html?/chb_e/stra/stra_01_03_03.html

## 1.2. Motivation

Continuous efforts are being made to ensure the securing of cargo on container ships by the shipbuilding companies and classification societies in order to minimize the container losses and cargo damages. As the trading through sea is getting more and more in demand, the shipping companies aspire to utilize their fleet in more optimized way and therefore, the demand of bigger vessels with more cargo capacity has increased. To cope up with this situation, classification societies have been continuously working on their rules and standards for newer and bigger vessels.

A ship observes lots of forces in the sea which generates different motions of the ship along different axes. Out of these motions, rolling motion of the ship is the most distinct form of movement because the ship has less resistance to movement along its longitudinal axis. This means that the ship rolling can occur easily even without significant weather conditions. Rolling can cause ship's speed reduction, negative impact on human health (sea-sickness) and adversely effects the ship's machinery.

With the increasing size of the container ships, the threat of extreme rolling and its consequences are building up a great challenge for the ship design offices and classification societies to ensure the safety to the maximum, especially for ultra-large container vessels ULCVs). Container ship rolling develops acceleration forces on the ship that can create heavy stresses in ship structure, on containers and their securing system. This could result in failure of securing system, damage of cargo and containers and even loss of containers. Therefore acceleration development need to be studied and analyzed for different sized container vessels in order to reduce its adverse impacts.

## 1.3. Problem Statement

For determining and analyzing container accelerations and to reduce their impact to the lowest to ensure cargo securement for all kind of vessels, DNV GL is effectively engaged to improve the rules especially for large container ships. In this thesis work, lateral accelerations exerted on the containers are to be analyzed since they have the biggest contribution in container shift and stack dislocation. This analysis has to be carried out with the help of DNV GL internal software ‘QUERROLL’ and ‘StowLash’.

QUERROLL codes have been developed to carry out hydrodynamic analysis of a ship and evaluate the lateral accelerations on the containers. These accelerations are formulated by an approximation formula which is developed by the software itself and is unique for every calculation. The formula in the code has been formulated by simulations performed for different ships at the time of its development. This formula has been used further in StowLash software to develop the approximation method responsible for the evaluation of lateral accelerations.

The accelerations are evaluated and analyzed from each software and a study is made to determine the feasibility of the approximation formula and the accuracy of the software for the new designed vessels with different lengths and cargo capacity.

## 1.4. Objectives

The study has been carried out for a range of vessels depending on the vessel size and container capacity. In this thesis work, six different container vessels ranging from cargo capacity of around 47 TEU to 20,000 TEU and length overall (LOA) of around 67 m to 400 m have been analyzed for the determination of lateral accelerations on the containers. The main objective has been divided into two major tasks which involves the comparison of acceleration study from the two provided software and determining the feasibility and effectiveness of the approximation formula for different sized vessels. Performing these tasks and analyzing the results would define the feasibility and effectiveness of the two software for newly design vessels and that would proclaim if there is a need to revise any of the software code.

### *1.4.1. Acceleration Comparison for Maximum Service Speed*

The first part of the study involves the evaluation of accelerations with speed input as the maximum service speed of the vessel. The results are formulated from the two software and with a constant speed for each vessel and a comparison is made to determine the difference in the results and to study the efficiency of approximation formula.

### *1.4.2. Acceleration Comparison for Reduced Speeds*

The second part of the study includes the comparison of accelerations for lower speeds of the ship. Different sized ships are analyzed to investigate the impact of reducing speed as input parameter in the two software. Later, the feasibility of approximation formula is determined in order to regulate its effectiveness for a range of lower speeds.

# 2. QUERROLL

QUERROLL is an internal software developed by DNV.GL. It is a hydrodynamic code which uses different program systems to formulate various parameters linked to ship motion in waves. Each program system is executed with an individual input file which then evaluate the output results. For the acceleration analysis, the most important task of QUERROLL is the development of an approximation formula which is then used to calculate the lateral accelerations for the defined positions.

## 2.1. Method of Analysis

QUERROLL is comprised of various program systems responsible for the calculation of different parameters related to hydrodynamics, ship motions and accelerations. Each program system has to be executed with an input file where the required data and parameters are defined. The analysis takes place in two major steps which involves the execution of all program systems.

### *2.1.1. Hydrodynamic Analysis*

The first step is to introduce and describe the ship details to the code. The initial input data for QUERROLL comprise;

1. Main ship data including dimensions, draft, weight tonnage and service speed.
2. Loading condition. It can perform evaluation for six different metacentric heights (GM) for a particular ship.
3. Bilge keel parameters.
4. Rudder position with aft perpendicular as origin and its main dimensions.

5. Hull lines for twenty frames. A range of twenty different frames is selected manually that describes efficiently the hull shape all across the longitudinal length of the ship. Each hull line for a particular frame is described by a range of points and each point is defined by its coordinates with the cross section origin lying at the keel base in the mid-breadth and the longitudinal origin lying on the aft perpendicular. x-coordinate describes the longitudinal position of the point along the ship’s length and y and z-coordinate describes the two dimensions of the cross section of the ship.
6. Inputs by default. There are some inputs that have been defined as default in the code. These includes;
   i. Wave statistic. This wave data is based on IACS Rec. No. 34 which includes scatter diagram and procedure for the formulation of rule load. IACS Rec. No. 34 is recommended and used by DNV.GL classification rules. It describes the wave data of the North Atlantic with the areas covered under 8,9,15 and 16 as defined in Figure 1.2.1.1.

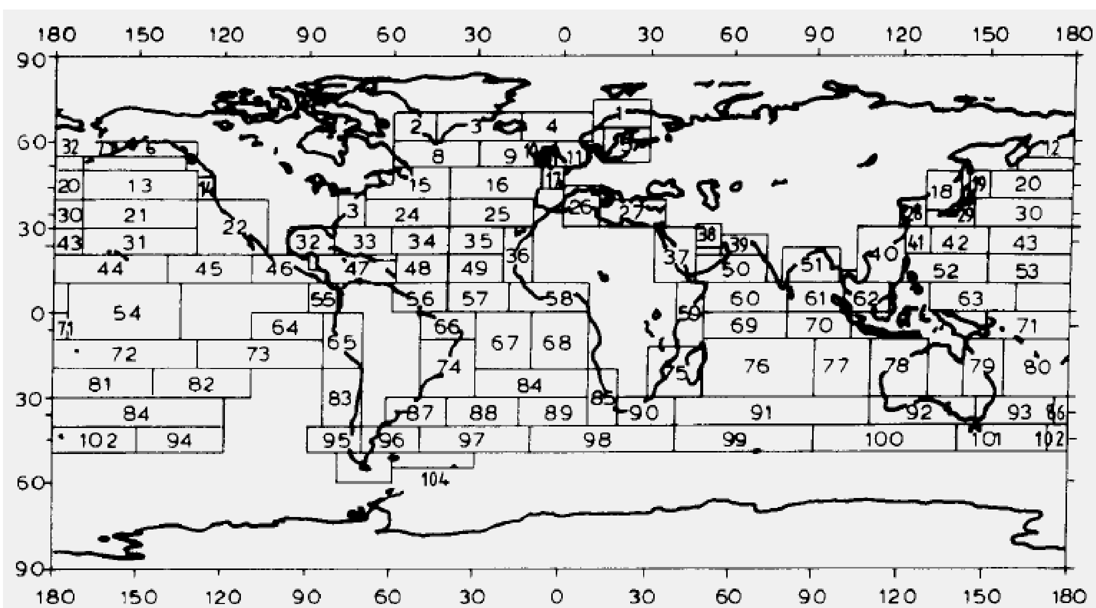



Figure 2.1. Division of sea areas. Available from www.iacs.org.uk – Standard wave data no. 34 – PDF

ii. Effective wave slope. This data has been calculated by a previously used program system of DNV.GL called STRIP2 which is based on the strip theory method.

**Strip theory** is a two-dimensional potential theory. For slender bodies, the fluid motion can be estimated as a two-dimensional problem. This theory can be applied to obtain an accurate estimate of the hydrodynamic forces. The basic methodology behind this theory is to reduce a three-dimensional hydrodynamic problem to a series of two-dimensional boundary value problems that are easier to solve. Figure 2.2 illustrates the idealization of the theory.

Strip theory takes into account that the variation of the flow is much larger in the cross-sectional plane as compared to the flow in the longitudinal direction of the ship. The technique used by strip theory involves dividing the submerged part of the vessel into a finite number of strips. This can compute 2-D hydrodynamic coefficients for added mass for each strip and then sum them up over the length of the vessel to yield the 3-D coefficients.

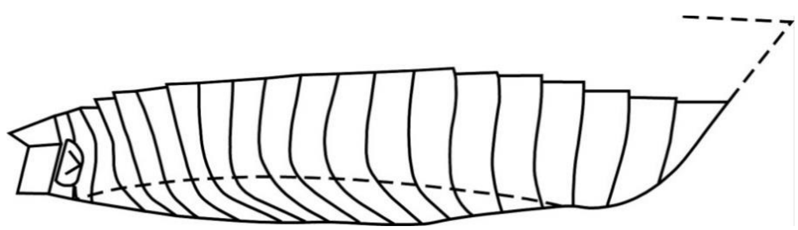


Figure 2.2. Strip theory idealization of a ship's hull. Available from 'Sea loads on ships and offshore structures' by O.M. Faltinsen

With these inputs, the hydrodynamic analysis in regular waves and statistic evaluation for maximum roll angle is performed using the program QRX of QUERROLL.

### *2.1.2. Acceleration Analysis*

For the evaluation of container accelerations, the ship's vertical and transverse accelerations are calculated first using the program STRIPSAS. Then the container accelerations are formulated with the program ACC which requires the following parameters to be defined as input;

1. Container positions. These are estimated from a preliminary general arrangement.
2. Main ship data including dimensions.
3. Roll motion parameters.
4. Ship's vertical and transverse accelerations.

QUERROLL performs the determination of accelerations by developing an approximation formula. This formula is based on the results and different formulae resulting from such QUERROLL simulations for more than 50 different container ships designs available in 2012

# 3. STOWLASH

StowLash is another internal software of DNV.GL. This software tool is mainly used to calculate the strength of the container lashing system for a particular stack of containers, based on DNV.GL's rules.

In this thesis work, StowLash has been used only to evaluate the accelerations of the containers. The accelerations are calculated in accordance with DNV.GL rules Pt. 5, Ch. 2, Sec. 8. Since the thesis work is only limited to container accelerations, therefore only the limited vessel information required by StowLash to evaluate the accelerations is used as input. This input data includes;

1. Main ship data including dimensions.
2. Longitudinal (x) position of center of gravity (LCG) of the particular stack with aft perpendicular being the origin.
3. Vertical (z) position of center of gravity of the lowest container of the stack with keel base being the origin.
4. Number of tiers of the particular stack. Number of rows is also required but StowLash require the number of rows as 1 to formulate the accelerations for the provided tiers.
5. Different loading conditions. StowLash can directly calculate accelerations for a provided metacentric height.

StowLash acceleration approximations are based on the formulae developed by QUERROLL simulations performed for various ships during its development and the approximation formula which will be observed in the discussion later, are actually used to develop the approximation method implemented in StowLash.

# 4. FORCES ON THE SHIP AND BEHAVIOUR

In this thesis work, the focus has been made on the accelerations produced by roll motion of the ship since the largest part of lateral acceleration is due to the ship's inclination, caused by roll motion and a wind induced heeling

## 4.1. Accelerations

The ship has six different motions;

- Surge – Forward/backward movement of ship, along with its length.
- Sway – Sideways movement of ship, along with its breadth.
- Heave – Up and down movement of the ship
- Roll – Sideways rotation of the ship's portside and starboard.
- Pitch – Up and down movement of the ship's stern or bow.
- Yaw – Side-to-side rotation of bow and stern of the ship.

Each of the above motions produces forces on the ship which are transferred to the stowed containers in the form of acceleration. These accelerations are represented in terms of gravitational acceleration ($m/s^2$). However, this thesis work is focused on accelerations produced by rolling of the ship.

Ship rolling generates acceleration forces that are tangent to the direction of inclination. The value of these forces increase with the distance from the roll axis. The containers stowed on the weather deck experience more accelerations as compared to the cargo hold and these accelerations increase with the height of stacks with maximum accelerations always on the top most tier. In case of steeper inclinations, there is a severe threat of cargo slippage. When the ship navigates in wave, the containers may be exposed to such accelerations for long periods resulting in catastrophic damage of the containers.

When a ship undergoes inclination, roll acceleration as well as horizontal and vertical acceleration contribute to the lateral accelerations produced on the containers.

Lateral acceleration $\ddot{y}$ is calculated by the equation 2-1 corresponding to the free body diagram in Figure 4.1. The Equation (2-1) (Daniel Abt, personal communication) is based on the assumption that roll angle $(\varphi)$, the vertical acceleration $(b_v)$ and the horizontal acceleration $(b_h)$ are simultaneously acting instantaneous values.

$$\ddot{y} = (g + b_v)\sin(\varphi) + b_h\cos(\varphi) + \left(\frac{2\pi}{T_\varphi}\right)^2 \varphi(z - z_\varphi) \quad (2\text{-}1)$$

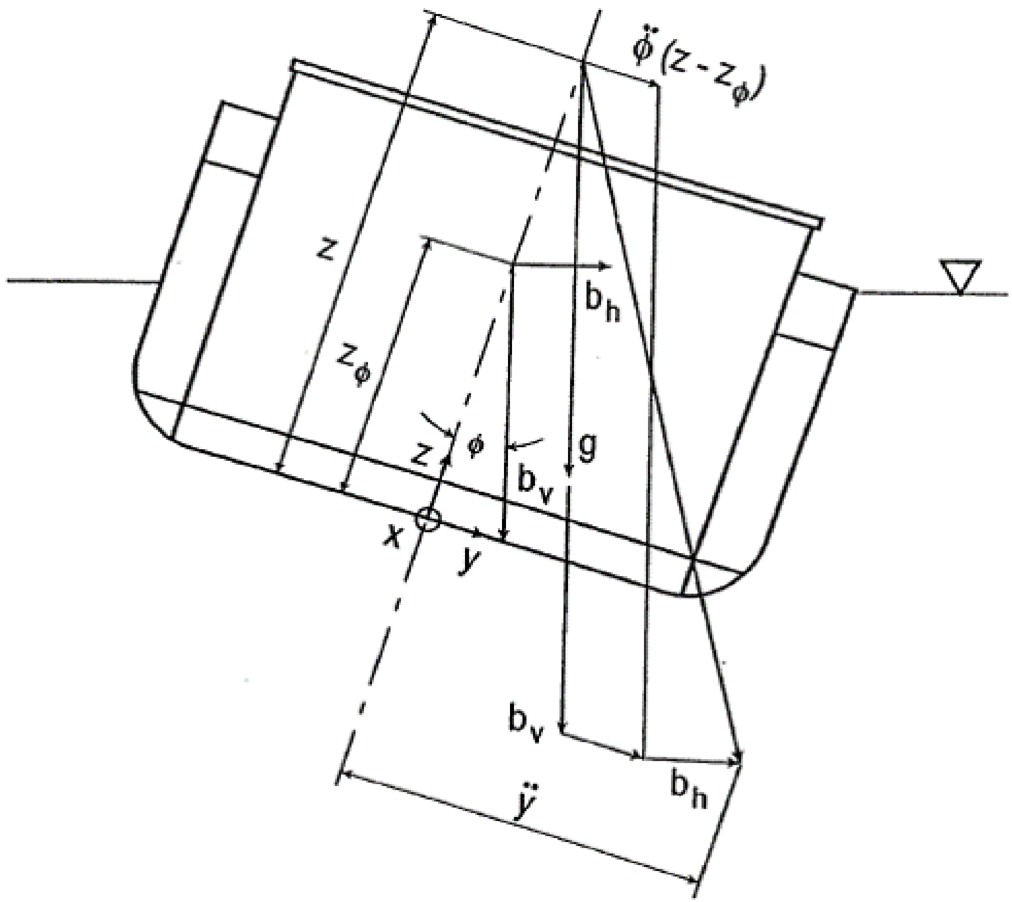



Figure 4.1. Free body diagram of a ship in rolling motion

Where, $g$ = Gravitational acceleration

$b_v$ = Vertical acceleration due to ship motion

$b_h$ = Horizontal acceleration due to ship motion

$\varphi$ = Roll angle

$T_\varphi$ = Roll period

$z$ = Vertical position of container above base

$z_\varphi$ = Vertical position of roll axis above base

Equation (2-1) is based on the assumption that the roll angle and vertical and horizontal accelerations are instantaneous values. However, the design values does not apply this assumption since they are maximum values and only occurs once in a ship's life. Therefore according to the DNV.GL rules, these parameters are served with stochastically independent values and do not have to be assumed as simultaneously maximum.

Equation (2-2) (Daniel Abt, personal communication) correlates the actual instantaneous values of $b_v$, $b_h$ and $\varphi$ to the design values of these parameters, denoted as $b_{vD}$, $b_{hD}$ and $\varphi_D$ respectively.

$$\left(\frac{b_v}{b_{vD}}\right)^2 + \left(\frac{b_h}{b_{hD}}\right)^2 + \left(\frac{\varphi}{\varphi_D}\right)^2 = 1 \qquad (2\text{-}2)$$

The horizontal accelerations $a_h$ and vertical accelerations $a_v$ are calculated by the program system STRIPSAS of QUERROLL using the formulae given in Equation (2-3) and (2-4) (Daniel Abt, personal communication).

- The corresponding acceleration parameter,

$$a_h = {}^{b_{hD}}/_{g} \qquad (2\text{-}3)$$

- The vertical acceleration parameter,

$$a_v = {}^{b_{vD}}/_{g} \tag{2-4}$$

One of the major reason of large accelerations near the ship's bow is the vertical acceleration $b_v$ contributes to the lateral acceleration indirectly via roll inclination.

## 4.2. Roll Period

The acceleration forces created by ship rolling are inversely proportion to the square of the rolling period. The roll period is given by the Weiss formula as shown in Equation (2-5). This formula correlates the ship roll period ($T_\varphi$) to the breadth of the ship and the metacentric height (*GM*).

$$T_\varphi = \frac{0.78B}{\sqrt{GM}} \tag{2-5}$$

Equation (2-5) illustrates that greater the metacentric height, shorter the roll period. Therefore ship undergoes large roll motions when it is rolling with a short natural roll period. This results in more initial stability of the ship and higher roll accelerations

The height of the roll axis from the base ($z_\varphi$) is also calculated by QUERROLL.

# 5. ANALYSIS ON QUERROLL FOR CONSTANT SPEED AS INPUT

In this thesis work, following six vessels of different length and cargo capacity have been investigated for acceleration analysis (Ship data provided by Daniel Abt, personal communication);

- Ship 1: 170 m long with 1900 TEU cargo capacity and constant draught of 9.5 m.
- Ship 2: 228 m long with 4000 TEU cargo capacity and constant draught of 12 m.
- Ship 3: 300 m long with 11,000 TEU cargo capacity and constant draught of 12.5 m.
- Ship 4: 400 m long with 20,120 TEU cargo capacity and constant draught of 14 m.
- Ship 5: 151 m long with 1100 TEU cargo capacity and constant draught of 6 m.
- Ship 6: 63 m long with 47 TEU cargo capacity and constant draught of 5.7 m.

The procedure and the effective parameters involved in the analysis have been defined and discussed under the ship 1 (1900 TEU) analysis. The same procedure and relative parameters are involved in the analysis for all the other ships. Therefore from ship 2 to ship 6, only the results are shown and a comparison is made for all the ships.

The lateral accelerations are formulated with speed input as the maximum service speed of the ship. Six different metacentric heights are considered ranging from low to high. Results for all the provided six metacentric heights are formulated by QUERROLL separately. Under the sub-heading of the ship 1, only the accelerations diagram and table for the highest considered metacentric height are shown and discussed while for other ships, the results for different metacentric heights are compared and discussed.

## 5.1. Ship 1 – 1900 TEU

For this ship, the hull lines for 20 frames starting from aft perpendicular were defined through points. These point were described using the coordinates with x-coordinate illustrating the longitudinal and y and z-coordinates illustrating the cross-section positions. For a particular frame, the x-coordinate for all the points was same since the frame position is constant regarding ship's length. Figure (5.1) shows the hull lines for 20 frames.

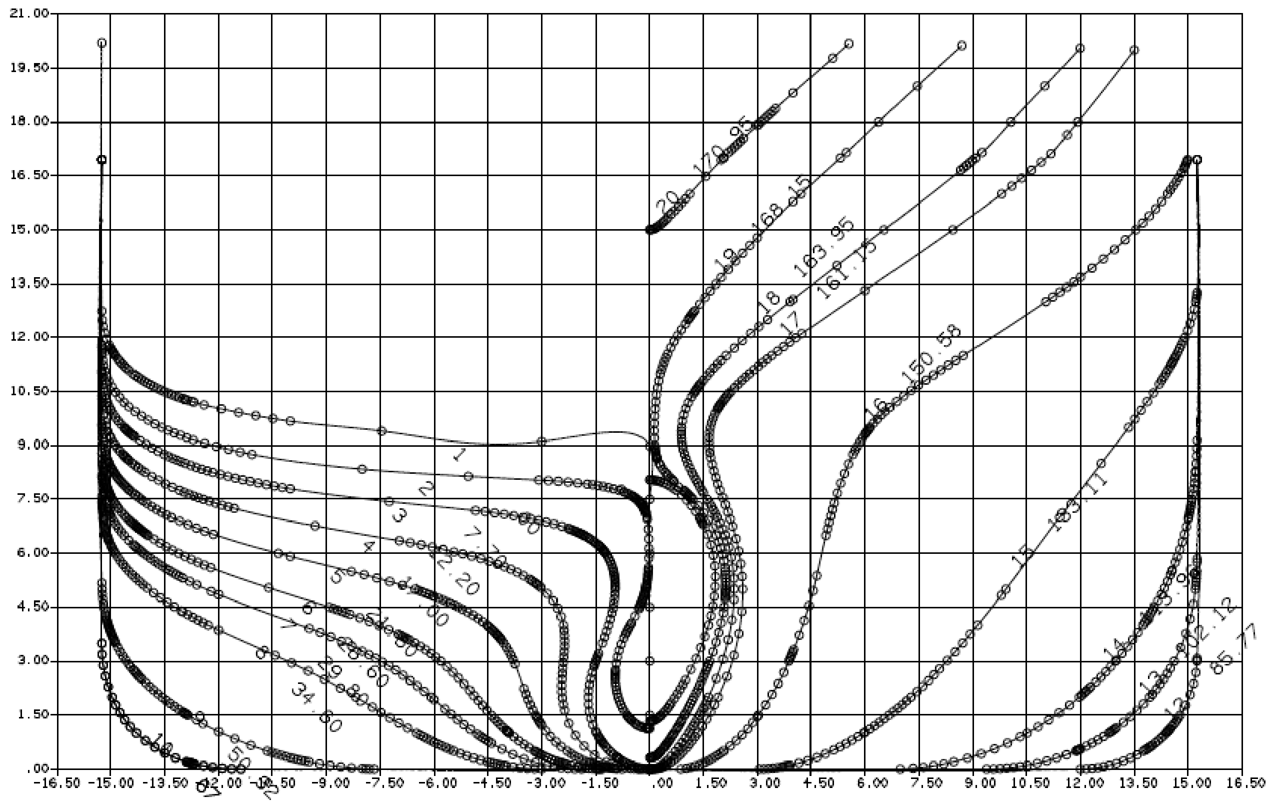



Figure 5.1. Ship 1 hull lines for 20 frames

The hull lines developed by QUERROLL utilizes interpolating curve since it actually passes through each control point. Due to this reason, for some frames at the stern of the ship that have hull and bulbous bow separated, the hull lines interpolated by QUERROLL glitched and the curve tried to join the bulbous bow and hull together.

In order to fix the sporadic curve formation at the bow frames, a knuckle point is introduced. A knuckle point is a point along a curve which makes a hard turn. Including a knuckle point makes the curve to exhibit discontinuous slope and therefore, the curvature also becomes discontinuous at that particular point.

Introducing knuckle points for such frames made the two parts of the hull separated and hence the hull line curves displayed the correct definition of the faulty frames (Figure 5.1).

The previous hull line formation without any fixes is shown in Figure 5.2 for 20 frames.

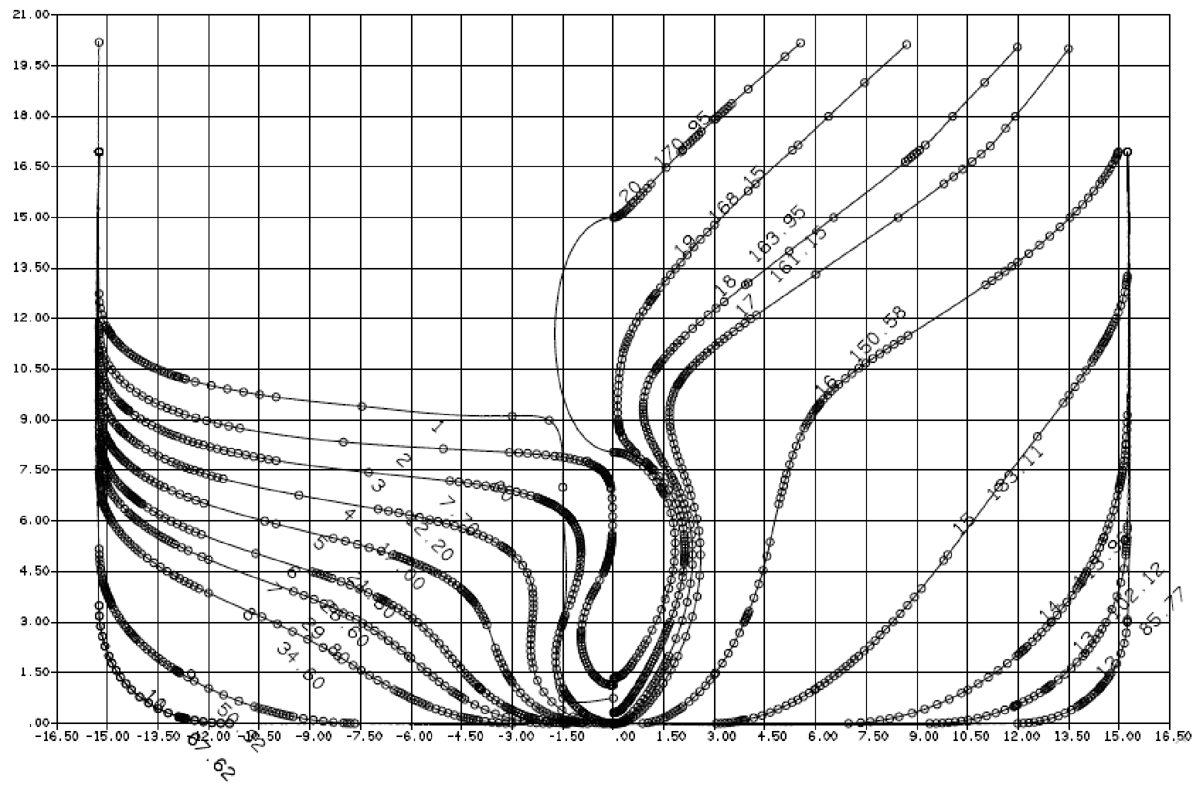



Figure 5.2. Inaccurate Ship 1 hull lines without knuckle points

### *5.1.1. Maximum Roll Angle and Roll Axis*

The hydrodynamic analysis is performed using program QRX. First, the evaluation for maximum roll angle is done by considering the actual hull lines for the frames. For the second part of analysis, a rudder is introduced as part of the frame in the aft most of the ship. This introduction can be seen in Figure 5.1 where hull line curve for frame number 1 drops down to the base of the ship illustrating a concept of rudder addition. Figure 5.3 and 5.4 shows the comparison for two different cases where it is observed that introduction of rudder created a small impact on the maximum roll angle and vertical position of the roll axis for lower GM, while at higher GM, the change is large comparatively.

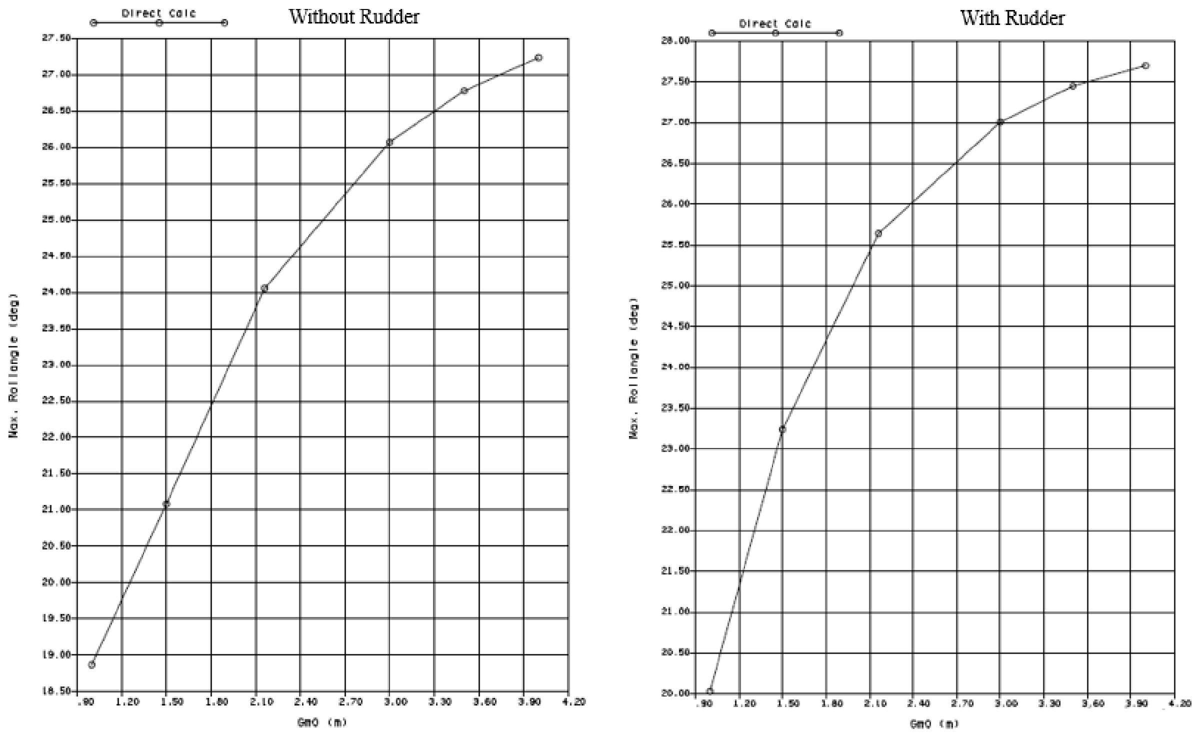



Figure 5.3. Comparison of max roll angles with and without rudder

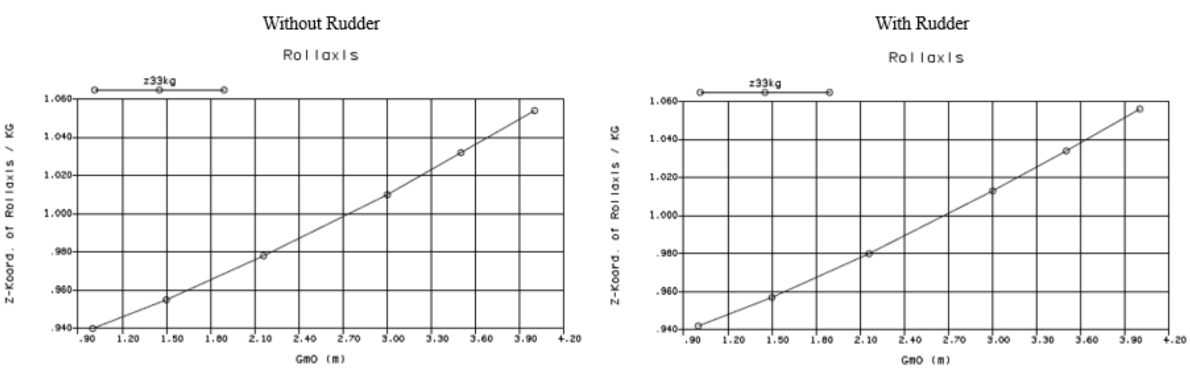



Figure 5.4. Comparison of roll axis height with and without rudder

Same step was performed for all range of vessels and for bigger sized vessels, the change in roll angles at higher GM was significant. Therefore, inclusion of rudder as part of hull line produced an impact and reduced the final acceleration output, though the decrement was noticeably less. Nevertheless, the rudder was introduced in the analysis for all the six ships

### *5.1.2. Lateral Accelerations*

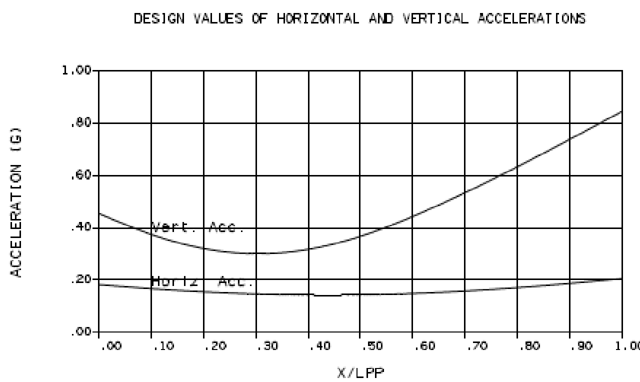
The software utilizes program ACC to evaluate the lateral accelerations of the z-coordinates of the stacks for the provided ship bays. The y-coordinate has no influence on the result. The results discussed in the Figure 5.5 shows the lateral accelerations for GM value of 4 m.

LATERAL ACCELERATION CALCULATION

CONTAINER VESSEL 1900 TEU-CLASS
CONTAINERS ON DECK AND IN HOLDS

DRAUGHT - 9.50 M
METACENTRIC HEIGHT GMO = 4.00 M
ROLL PERIOD Troll - 11.46 S

DESIGN VALUES:
HORIZONTAL ACCELERATION ) SEE
VERTICAL ACCELERATION ) FIG.
ROLL ANGLE - 27.7 DEG




CALCULATED LATERAL ACCELERATIONS IN G

| | BAY 35 HOLD7F | BAY 33 HOLD6A | BAY 31 HOLD6F | BAY 29 HOLD5A | BAY 27 HOLD5F | BAY 25 HOLD4A | BAY 23 HOLD4F | BAY 21 HOLD6A | BAY 19 HOLD6F | BAY 17 HOLD5A | BAY 15 HOLD5F | BAY 13 HOLD4A | BAY 11 HOLD4F | BAY 09 HOLD3A | BAY 07 HOLD3F | BAY 05 HOLD2A | BAY 03 HOLD2F | BAY 01 HOLD3F |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| X (M) | 20.40 | 24.50 | 37.53 | 41.60 | 54.12 | 57.20 | 69.21 | 73.30 | 87.43 | 91.50 | 105.53 | 109.10 | 123.00 | 126.77 | 139.88 | 144.50 | 156.00 | 160.20 |
| TIER NO.13 | .9558 | .9543 | .9688 | .9682 | .9671 | .9672 | .9679 | .9688 | | | | | | | | | | |
| TIER NO.12 | .9185 | .9171 | .9313 | .9307 | .9296 | .9297 | .9304 | .9313 | .9351 | .9368 | .9436 | .9458 | .9551 | .9580 | | | | |
| TIER NO.11 | .8813 | .8798 | .8940 | .8933 | .8921 | .8922 | .8929 | .8939 | .8978 | .8996 | .9066 | .9089 | .9186 | .9215 | .9329 | .9372 | .9487 | .9532 |
| TIER NO.10 | .8443 | .8427 | .8566 | .8560 | .8547 | .8548 | .8556 | .8566 | .8606 | .8624 | .8698 | .8721 | .8821 | .8852 | .8968 | .9013 | .9132 | .9178 |
| TIER NO. 9 | .8073 | .8057 | .8194 | .8187 | .8173 | .8175 | .8183 | .8193 | .8235 | .8255 | .8330 | .8354 | .8457 | .8489 | .8609 | .8656 | .8777 | .8824 |
| TIER NO. 8 | .7705 | .7688 | .7823 | .7816 | .7801 | .7803 | .7811 | .7822 | .7866 | .7886 | .7964 | .7989 | .8095 | .8129 | .8252 | .8300 | .8425 | .8473 |
| TIER NO. 7 | .7338 | .7320 | | | | | | | | | | | | | | | | |
| TIER NO. 6 | | | .6963 | .6955 | .6939 | .6941 | .6950 | .6962 | .7010 | .7032 | .7118 | .7145 | .7261 | .7296 | .7429 | .7480 | .7961 | .8712 |
| TIER NO. 5 | | | .6596 | .6588 | .6571 | .6573 | .6583 | .6595 | .6645 | .6668 | .6757 | .6786 | .6905 | .6943 | .7079 | .7132 | .7615 | .8361 |
| TIER NO. 4 | | | .6232 | .6223 | .6206 | .6207 | .6217 | .6230 | .6283 | .6307 | .6399 | .6428 | .6553 | .6591 | .6732 | .6786 | .7270 | .8013 |
| TIER NO. 3 | | | .5870 | .5860 | .5842 | .5843 | .5854 | .5867 | .5923 | .5947 | .6044 | .6074 | .6203 | .6243 | .6388 | .6444 | .6928 | |
| TIER NO. 2 | | | .5510 | .5500 | .5481 | .5482 | .5493 | .5507 | .5565 | .5591 | .5691 | .5723 | .5856 | .5897 | .6047 | .6105 | .6589 | |
| TIER NO. 1 | | | .5153 | .5143 | .5122 | .5124 | .5135 | .5150 | .5210 | .5237 | .5342 | .5375 | .5513 | .5555 | .5710 | .5769 | | |

APPROXIMATION FORMULA AY - .49092 + .014025*Z + .18003*( X /169.5M - .31999 ) **2

Figure 5.5. Lateral accelerations for 4 m GM

The Figure 5.5 displays the design values of accelerations for the ship. The maximum value which is always on the weather deck at the top most tier, is the design value for the lateral acceleration for a given position.

The draught is kept constant as design draught and the roll angle given is valid for the whole ship. The horizontal and vertical accelerations are represented as a diagram illustrating the variation of accelerations over the ship length. The maximum values of lateral accelerations have been formulated in the lower table for all the stacks regarding the bays defined. These have been evaluated by an appropriate combination of horizontal acceleration, vertical acceleration and roll angle.

The bottom most part of the figure displays the approximation formula generated by QUERROLL for the defined input values. The general form of the formula is given in Equation (5-1).

$$a_y = a_{yo} + a_{yz}\,.\,z + a_{yxz}\,.\left( {}^{x}\!/_{L_{pp}} - b \right)^2 \qquad (5\text{-}1)$$

In order to have a view on the usage of the approximation formula created by QUERROLL, the acceleration is manually calculated using the formula for the position at tier number 13 and bay number 35 having a longitudinal center of gravity as 20.4 m. The formula developed by QUERROLL for the particular condition given in Figure 5.5 is represented by Equation (5-2)

$$A_Y = 0.49092 + (0.014025 \times Z) + 0.18003 \times (X/169.5 - 0.31999)^2 \qquad (5\text{-}2)$$

Where,

- $A_Y$ is the lateral acceleration in G.
- $Z$ is the vertical center of gravity for the particular position, estimated to be 32.72 m.
- $X$ is the longitudinal center of gravity for the particular position, estimated to be 20.4 m.

Using the above defined values in Equation (3-2) and solving for $A_Y$,

$$A_Y = 0.9567\,.\,G$$

While from the table given in Figure 5.5, the value is calculated to be 0.9558 .G which is almost equal to the value calculated manually. The small difference is due to the slight inaccuracies as the real positions formulated by QUERROLL may differ in the range of several cm from positions used in manual calculation in Equation (5-2).

The diagram for the design values of horizontal and vertical acceleration in Figure 5.5 illustrates that the accelerations at the either end of the ship are greater than midship. The vertical acceleration contributes indirectly with the roll inclination of the ship. Also due to direct interaction of ship's bow with waves for most of the time while the ship navigates through seaways, more and maximum forces are exerted at the bow region resulting in the occurrence of high accelerations. For the same reason, high vertical and horizontal accelerations are seen in the foremost part of the ship, ultimately resulting in high lateral accelerations.

#### *5.1.2.1. Comparison for Different Metacentric Heights*

The output by QUERROLL gives lateral accelerations for six defined metacentric heights that includes 1 m, 1.5 m, 2.16 m, 3 m, 3.5 m and 4 m GM. For the study, the maximum acceleration which is always on the top most tier is considered from three longitudinal positions including bay 35 from aft part, bay 21 from midship and bay 1 from fore part of the ship. Table 5.1 shows the maximum acceleration values for three different bays occurring on the top most tier of the relative bay across the ship. The results have been calculated for six different metacentric heights.

Table 5.1. Maximum accelerations for maximum service speed and different metacentric heights

| | Maximum Accelerations (x G) | | |
|---|---|---|---|
| GM (m) | Aft Bay (35) | Mid Bay (21) | Fore Bay (1) |
| 1 | 0.4873 | 0.4834 | 0.5274 |
| 1.5 | 0.5965 | 0.5958 | 0.6337 |
| 2.16 | 0.7135 | 0.7168 | 0.7425 |
| 3 | 0.8324 | 0.8403 | 0.8475 |
| 3.5 | 0.8963 | 0.9068 | 0.9027 |
| 4 | 0.9558 | 0.9688 | 0.9532 |

Similarly, the graph in Figure 5.6 illustrates the comparison for the acceleration values for different bays and for tier number 11 since the considered fore bay has the stack height up to only 11 tiers. It can be seen from the graph that the accelerations gets higher with the increasing GM while the accelerations for the fore bay are the highest comparatively, reason being that the ship's bow gets hit by the waves during navigation.

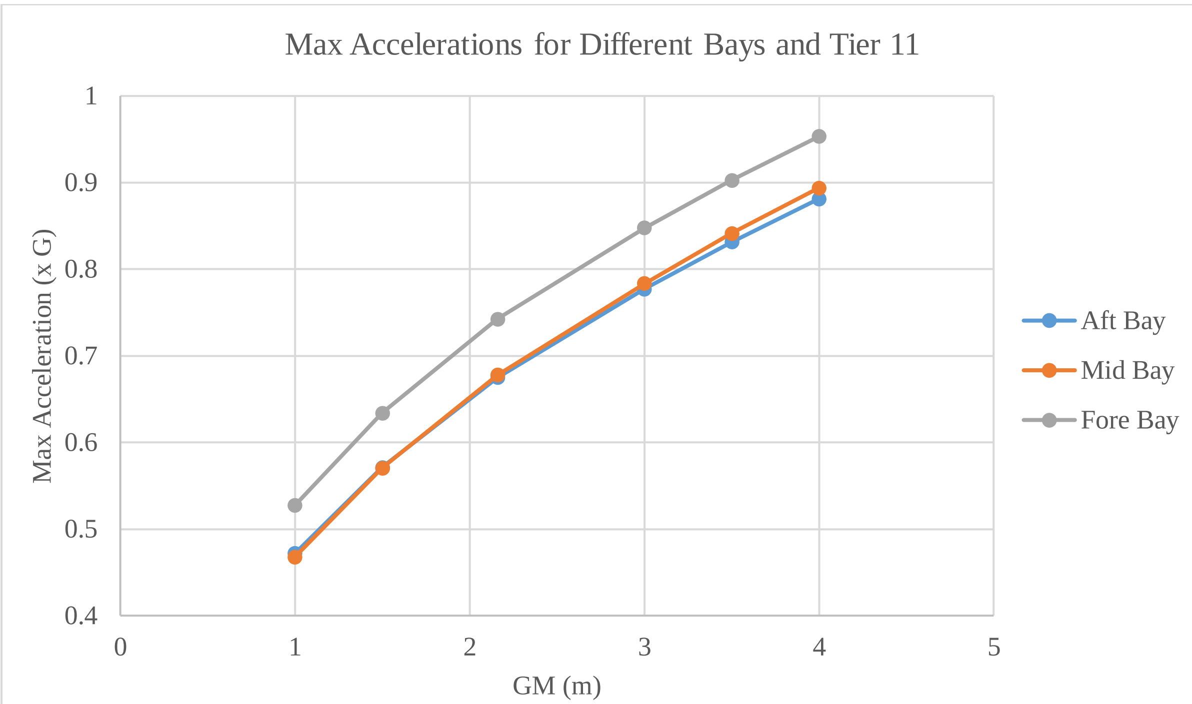



Figure 5.6. Comparison of accelerations for different longitudinal positions at tier no. 11

### *5.1.3. Parametric Roll Motions*

As the ship moves up and down in the wave, the GM varies due to rolling and pitching of the ship. The change in buoyancy and wave excitation forces combines to push the ship to either side. This synchronous motion leads heavy rolling that may reach considerable amplitudes. This phenomenon is known as 'parametric roll motion'. The most critical conditions linked to this type of motion are;

- The encounter period is half of the roll period

- The wavelength is almost equal to the ship's length.

Figure 5.7 shows the range of critical speed over the metacentric height.

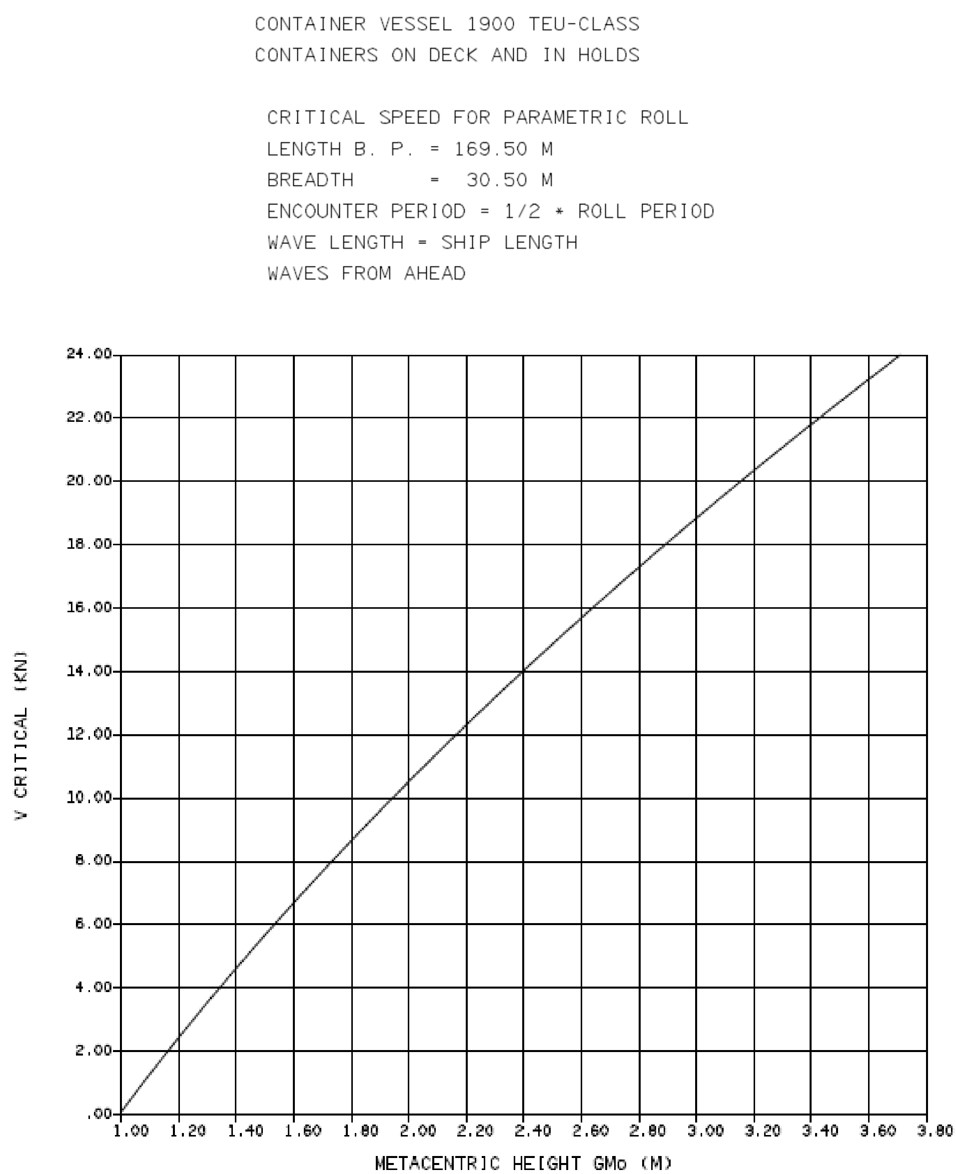



Figure 5.7. Range of critical speed for parametric roll

The ship motion causing parametric roll is different from the normal wave induced roll motion since it occurs very rarely and the probability that such motion occurs is very difficult to evaluate. Therefore this phenomenon is not considered to be a significant contributor to the lateral accelerations and hence is considered of minor importance. For the same reason, the parametric roll motion in not included in the analysis in this thesis work.

### *5.1.4. Importance of bilge keel data*

Bilge keel data as input for hydrodynamic analysis exhibits a critical role in determining the maximum roll angle and accelerations. Length and breadth of bilge keel and bilge radius should be defined perfectively. A slight difference in these parameters' value could result in drastic change in the hydrodynamic analysis and accelerations output.

Another input named as 'z' parameter for roll damping has a significant contribution in the output results. It depends on the profile shape of bilge keel and the value is estimated as 1.5 for flat bar and 2.0 for L-profile.

## 5.2. Ship 2 – 4000 TEU

Figure 5.8 illustrates the hull lines for the defined 20 frames. Same remedies were applied as for ship 1 to eliminate all the irregularities in the hull lines. In addition, due to the nature of interpolating curves, some of the horizontal and vertical frame lines were bulging out of the defined breadth and depth of the ship. Therefore to enforce and fix the lines under the limit, frame line slope was defined as 0 degrees for horizontal lines and 90 degrees for vertical lines.

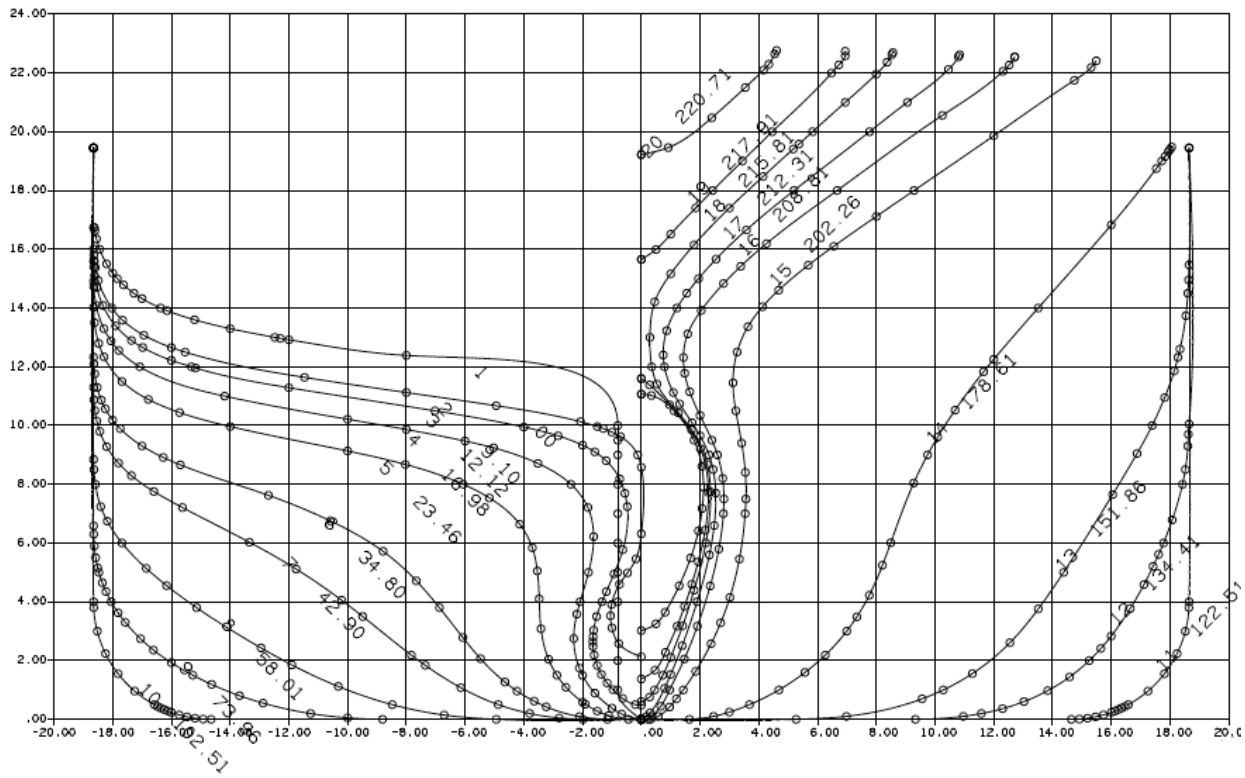



Figure 5.8. Ship 2 hull lines for 20 frames

### *5.2.1. Maximum Roll Angle and Roll Axis*

Figure 5.9 and 5.10 shows the maximum roll angle increasing with the metacentric height and the height of the roll axis above the keel base of the ship, respectively.

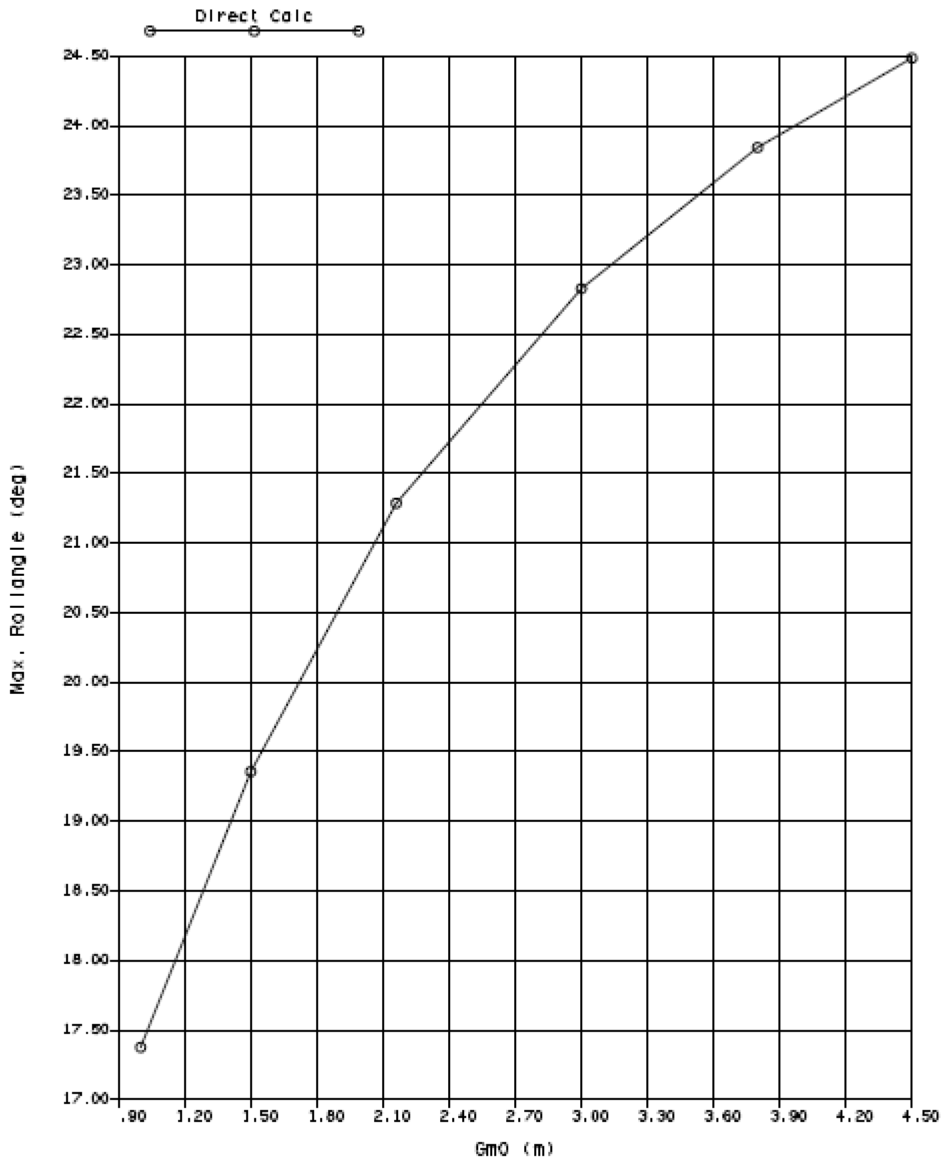



Figure 5.9. Maximum roll angle over a range of GM

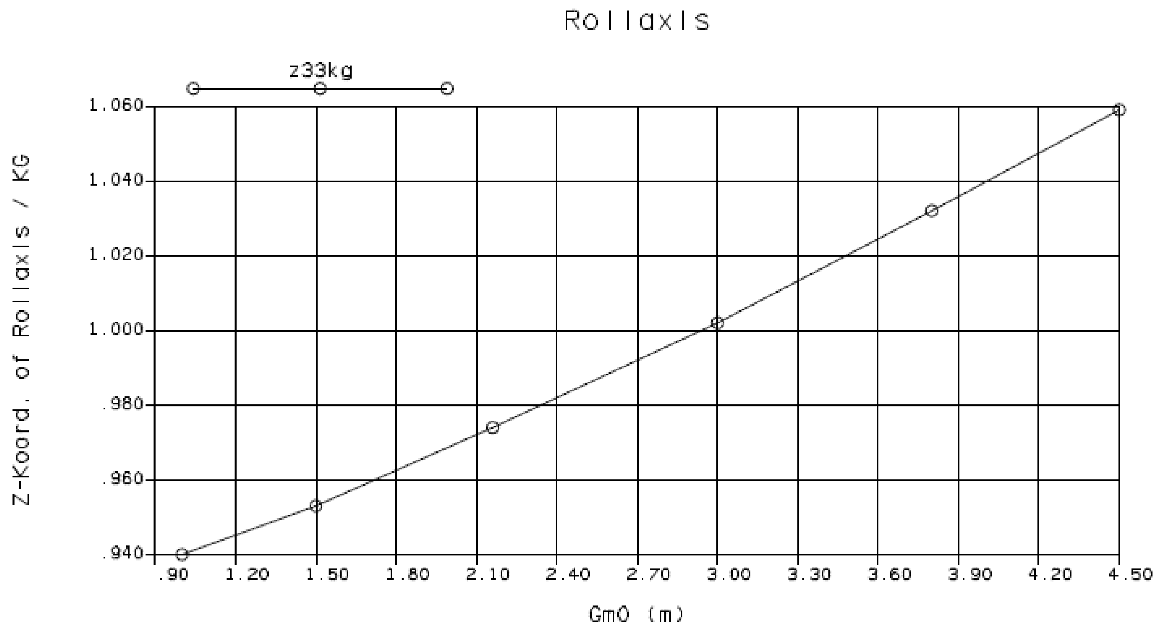



Figure 5.10. Height of roll axis above base

### *5.2.2. Lateral Accelerations*

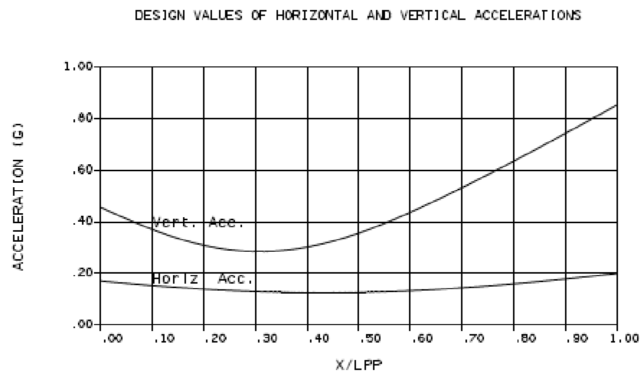
Figure 5.11 shows the accelerations and roll parameters for 4.5 m GM that is the highest considered metacentric height. The vertical and horizontal accelerations can be noted to have the highest values at fore part of ship, followed by aft and mid part.

LATERAL ACCELERATION CALCULATION

CONTAINER VESSEL 3800 TEU-CLASS
CONTAINERS ON DECK AND IN HOLDS

DRAUGHT - 12.00 M
METACENTRIC HEIGHT GMO = 4.50 M
ROLL PERIOD Troll - 13.18 S

DESIGN VALUES:
HORIZONTAL ACCELERATION ) SEE
VERTICAL ACCELERATION ) FIG.
ROLL ANGLE - 24.5 DEG




CALCULATED LATERAL ACCELERATIONS IN G

| | BAY 50 - | BAY 46 HLD10A | DECKS-HOUSE | BAY 43 HOLD9F | BAY 41 HOLD8A | BAY 39 HOLD8F | BAY 37 HOLD7A | BAY 35 HOLD7F | BAY 33 HOLD6A | BAY 31 HOLD6F | BAY 29 HOLD5A |
|---|---|---|---|---|---|---|---|---|---|---|---|
| X (M) | 2.00 | 12.40 | 25.00 | 33.10 | 43.30 | 53.70 | 63.90 | 73.40 | 83.60 | 93.10 | 103.30 |
| TIER NO.15 | | | | .8111 | .8084 | .8067 | .8054 | .8050 | .8052 | .8057 | .8073 |
| TIER NO.14 | .7873 | .7825 | | .7862 | .7834 | .7818 | .7804 | .7800 | .7802 | .7807 | .7823 |
| TIER NO.13 | .7628 | .7579 | | .7614 | .7585 | .7568 | .7555 | .7550 | .7552 | .7557 | .7574 |
| TIER NO.12 | .7384 | .7335 | | .7367 | .7337 | .7319 | .7305 | .7300 | .7302 | .7307 | .7325 |
| TIER NO.11 | .7142 | .7090 | | .7119 | .7089 | .7070 | .7056 | .7051 | .7053 | .7058 | .7077 |
| TIER NO.10 | .6899 | .6846 | | .6873 | .6841 | .6822 | .6808 | .6802 | .6805 | .6810 | .6829 |
| TIER NO. 9 | .6658 | .6604 | | .6628 | .6594 | .6575 | .6560 | .6555 | .6557 | .6562 | .6582 |
| TIER NO. 8 | .6418 | .6362 | | | | | | | | | |
| TIER NO. 7 | | | | .6085 | .6049 | .6028 | .6012 | .6006 | .6009 | .6014 | .6035 |
| TIER NO. 6 | | | | .5842 | .5805 | .5783 | .5766 | .5760 | .5763 | .5769 | .5790 |
| TIER NO. 5 | | | | .5601 | .5562 | .5539 | .5522 | .5515 | .5518 | .5524 | .5546 |
| TIER NO. 4 | | | | .5360 | .5320 | .5297 | .5278 | .5271 | .5274 | .5280 | .5304 |
| TIER NO. 3 | | | | .5121 | .5079 | .5055 | .5036 | .5029 | .5031 | .5038 | .5062 |
| TIER NO. 2 | | | | .4883 | .4840 | .4815 | .4795 | .4787 | .4790 | .4797 | .4822 |
| TIER NO. 1 | | | | .4647 | .4603 | .4576 | .4555 | .4547 | .4550 | .4557 | .4582 |

| | BAY 27 HOLD5F | BAY 25 HOLD4A | BAY 23 HOLD4F | BAY 21 HOLD6A | BAY 19 HOLD6F | BAY 17 HOLD5A | BAY 15 HOLD5F | BAY 13 HOLD4A | BAY 11 HOLD4F | BAY 09 HOLD3A | BAY 07 HOLD3F | BAY 05 HOLD2A | BAY 03 HOLD2F | BAY 01 HOLD3F |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| X (M) | 113.80 | 123.00 | 133.50 | 143.70 | 153.20 | 163.40 | 173.90 | 183.10 | 189.60 | 193.80 | 198.30 | 205.50 | 213.00 | 223.20 |
| TIER NO.15 | | | | | | | | | | | | | | |
| TIER NO.14 | .7842 | .7870 | .7904 | .7946 | .7991 | .8043 | | | | | | | | |
| TIER NO.13 | .7593 | .7622 | .7658 | .7701 | .7746 | .7799 | .7862 | .7920 | .7964 | .7994 | .8026 | .8078 | .8138 | .8219 |
| TIER NO.12 | .7345 | .7374 | .7411 | .7455 | .7502 | .7557 | .7621 | .7680 | .7725 | .7756 | .7788 | .7842 | .7902 | .7986 |
| TIER NO.11 | .7097 | .7127 | .7165 | .7210 | .7258 | .7315 | .7381 | .7440 | .7487 | .7518 | .7552 | .7607 | .7667 | .7752 |
| TIER NO.10 | .6849 | .6881 | .6920 | .6967 | .7016 | .7073 | .7140 | .7202 | .7250 | .7282 | .7316 | .7372 | .7434 | .7520 |
| TIER NO. 9 | .6603 | .6635 | .6675 | .6724 | .6774 | .6833 | .6902 | .6965 | .7014 | .7046 | .7081 | .7138 | .7201 | .7290 |
| TIER NO. 8 | | | | | | | | | | | | | | |
| TIER NO. 7 | .6057 | .6093 | .6136 | .6187 | .6241 | .6303 | .6376 | .6442 | .6494 | .6528 | .6564 | .6624 | .7150 | .7701 |
| TIER NO. 6 | .5814 | .5850 | .5894 | .5947 | .6002 | .6066 | .6141 | .6209 | .6261 | .6296 | .6333 | .6394 | .6920 | .7470 |
| TIER NO. 5 | .5570 | .5608 | .5653 | .5708 | .5764 | .5831 | .5907 | .5976 | .6030 | .6066 | .6104 | .6168 | .6690 | .7239 |
| TIER NO. 4 | .5329 | .5367 | .5414 | .5470 | .5528 | .5596 | .5675 | .5746 | .5801 | .5837 | .5876 | .5940 | .6462 | |
| TIER NO. 3 | .5088 | .5128 | .5176 | .5234 | .5294 | .5364 | .5444 | .5517 | .5573 | .5610 | .5650 | .5714 | .6235 | |
| TIER NO. 2 | .4848 | .4890 | .4940 | .4999 | .5061 | .5133 | .5215 | .5289 | .5347 | .5384 | .5425 | .5492 | | |
| TIER NO. 1 | .4610 | .4653 | .4705 | .4766 | .4829 | .4903 | .4988 | .5064 | .5123 | .5161 | .5203 | .5270 | | |

APPROXIMATION FORMULA AY - .44056 + .009301*Z + .18453*( X /228.0M - .33184 ) **2

Figure 5.11. Lateral accelerations for 4.5 m GM

It can be viewed from the figure that the vertical acceleration graph abruptly climbs to the higher accelerations as the ship’s length reaches the bow of the ship. This is one of the major reasons for getting higher lateral accelerations at fore part of the ship.

### *5.2.2.1. Comparison for Different Metacentric Heights*

The maximum accelerations for three different longitudinal positions for different GMs are represented in Table 5.2. The values selected are for three bays that includes aft bay 46, mid bay 29 and fore bay 1. Figure 5.12 shows the graph for comparison of the accelerations for these bays at tier number 13.

Table 5.2. Maximum accelerations for maximum service speed and different metacentric heights

| | Maximum Accelerations (x G) | | |
|---|---|---|---|
| GM (m) | Aft Bay (46) | Mid Bay (29) | Fore Bay (1) |
| 1 | 0.4142 | 0.405 | 0.4602 |
| 1.5 | 0.4783 | 0.4738 | 0.5258 |
| 2.16 | 0.556 | 0.558 | 0.6037 |
| 3 | 0.6422 | 0.6524 | 0.688 |
| 3.8 | 0.7189 | 0.7369 | 0.7615 |
| 4.5 | 0.7825 | 0.8073 | 0.8219 |

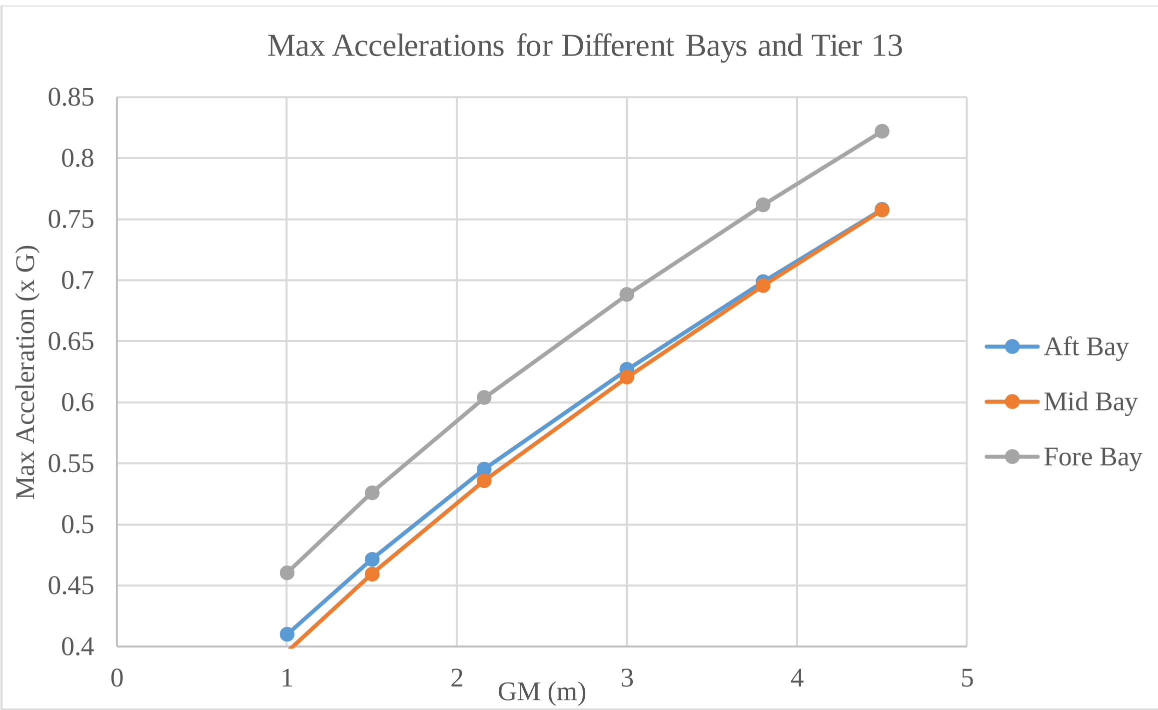



Figure 5.12. Comparison of accelerations for different longitudinal positions at tier no. 13

## 5.3. Ship 3 – 11,000 TEU

This ship with an estimated cargo capacity of 11,000 TEU falls in the category of ultra large container ship (ULCS). Figure 5.13 displays the hull line of the ship described by 20 frames.

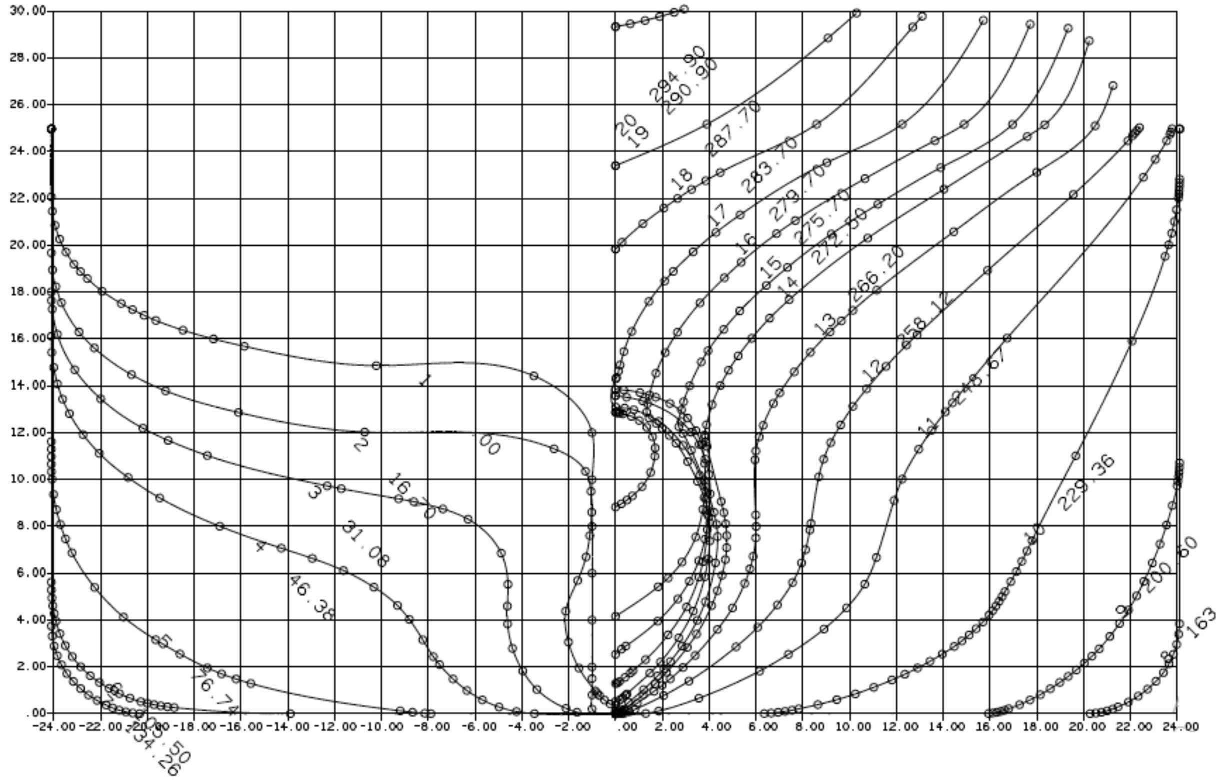



Figure 5.13. Ship 3 hull lines for 20 frames

### *5.3.1. Maximum Roll Angle and Roll Axis*

Figure 5.14 and 5.15 shows the maximum roll angle and height of roll axis above keel base, respectively. The results are distributed for a provided range of GM from low to high.

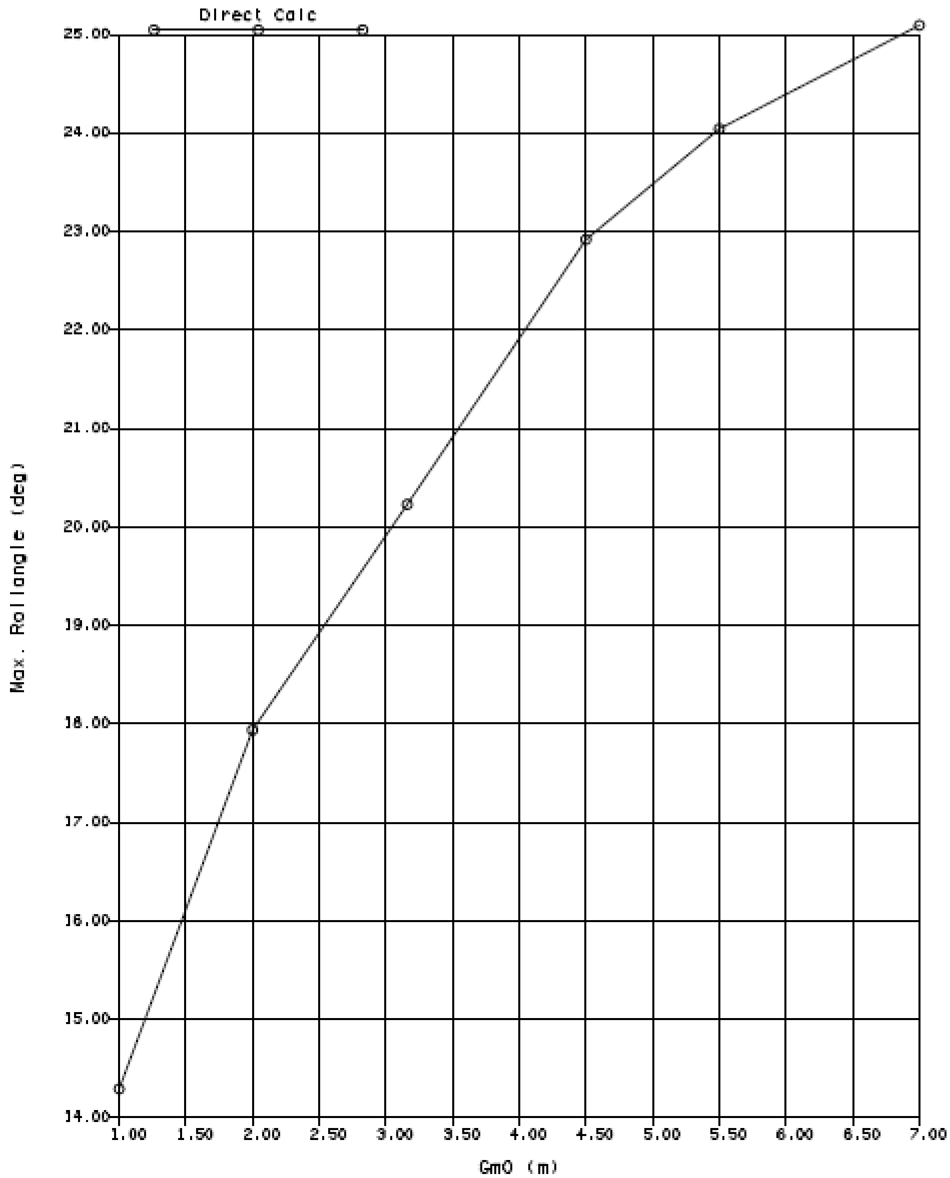



Figure 5.14. Max roll angle over a range of GM

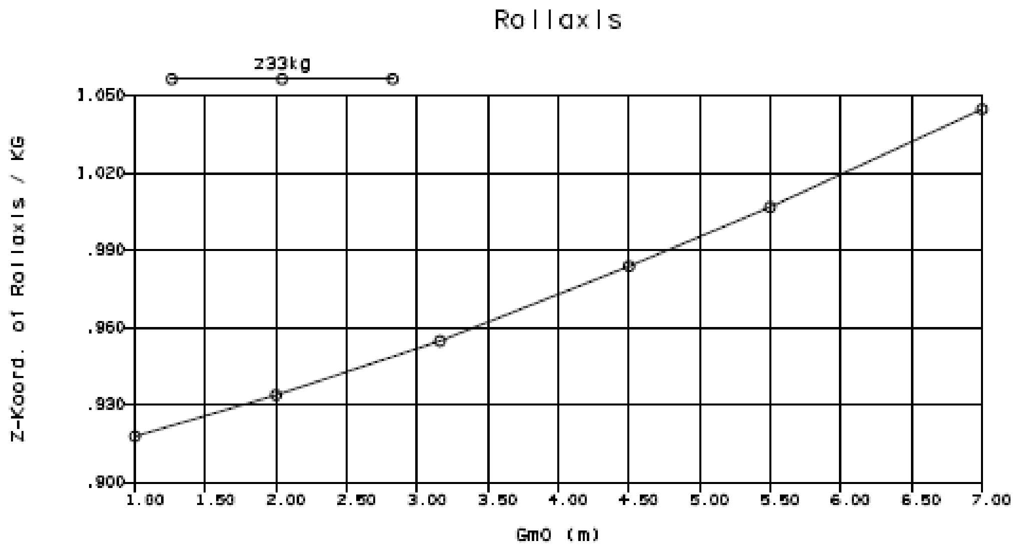



Figure 5.15. Height of roll axis above base

### *5.3.2. Lateral Accelerations*

Figure 5.16 shows the chart illustrating the lateral accelerations for the highest considered GM of 7 m. It also displays the graph showing the design values of vertical and horizontal accelerations distributed along the length of the ship.

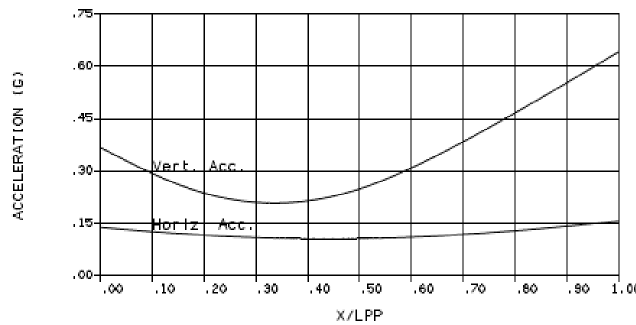
LATERAL ACCELERATION CALCULATION

CONTAINER VESSEL 10926 TEU-CLASS
CONTAINERS ON DECK AND IN HOLDS

DRAUGHT - 12.50 M
METACENTRIC HEIGHT GMO = 7.00 M
ROLL PERIOD Troll - 13.75 S

DESIGN VALUES:
HORIZONTAL ACCELERATION ) SEE
VERTICAL ACCELERATION ) FIG.
ROLL ANGLE - 25.1 DEG

DESIGN VALUES OF HORIZONTAL AND VERTICAL ACCELERATIONS




CALCULATED LATERAL ACCELERATIONS IN G

| | BAY 70 HLD10A | BAY 67 HLD10A | BAY 65 HLD10A | BAY 63 HLD10A | BAY 61 HLD10A | ENGINE FUNNEL | BAY 51 HOLD7A | BAY 49 HOLD7F | BAY 47 HOLD6A | BAY 45 HOLD6F | BAY 43 HOLD5A | BAY 41 HOLD5F | BAY 39 HOLD4A | BAY 37 HOLD4F | BAY 35 HOLD6A | BAY 33 HOLD6F | BAY 31 HOLD5A | BAY 29 HOLD5F | BAY 27 HOLD4A | BAY 25 HOLD4F | DECK - HOUSE | BAY 23 HOLD3A | BAY 21 HOLD3F | BAY 11 HOLD3F | BAY 09 HOLD2A | BAY 07 HOLD2F | BAY 05 HOLD3F | BAY 03 HOLD2F | BAY 01 HOLD3F |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| X (M) | 2.69 | 13.63 | 19.76 | 28.01 | 34.14 | 43.00 | 79.97 | 86.11 | 94.36 | 100.48 | 108.73 | 114.86 | 123.11 | 129.24 | 137.49 | 143.62 | 151.67 | 158.01 | 166.25 | 172.38 | 181.00 | 191.23 | 197.36 | 234.37 | 240.50 | 246.75 | 254.88 | 263.13 | 269.26 |
| TIER NO.22 | | .9760 | .9748 | .9514 | | | .9679 | .9676 | .9673 | .9673 | .9673 | .9673 | .9674 | .9677 | .9681 | .9684 | .9689 | .9696 | .9706 | .9713 | | .9742 | | | | | | | |
| TIER NO.21 | | .9522 | .9511 | .9277 | .9267 | | .9440 | .9437 | .9434 | .9434 | .9434 | .9433 | .9435 | .9438 | .9442 | .9445 | .9451 | .9458 | .9467 | .9474 | | .9504 | .9515 | | | | | | |
| TIER NO.20 | .9092 | .9285 | .9273 | .9039 | .9030 | | .9202 | .9198 | .9196 | .9195 | .9195 | .9194 | .9196 | .9199 | .9203 | .9206 | .9212 | .9219 | .9228 | .9236 | | .9267 | .9279 | .9365 | .9381 | .9406 | .9425 | .9450 | |
| TIER NO.19 | .8856 | .9049 | .9036 | .8802 | .8792 | | .8963 | .8959 | .8956 | .8956 | .8956 | .8955 | .8957 | .8960 | .8964 | .8968 | .8973 | .8981 | .8991 | .8999 | | .9030 | .9042 | .9130 | .9147 | .9172 | .9191 | .9218 | .9238 |
| TIER NO.18 | .8621 | .8813 | .8800 | .8566 | .8555 | | .8724 | .8720 | .8718 | .8717 | .8717 | .8717 | .8718 | .8721 | .8726 | .8729 | .8735 | .8742 | .8753 | .8761 | | .8793 | .8805 | .8895 | .8913 | .8939 | .8958 | .8986 | .9006 |
| TIER NO.17 | .8386 | .8577 | .8564 | .8329 | .8319 | | .8486 | .8482 | .8479 | .8479 | .8478 | .8478 | .8479 | .8483 | .8488 | .8491 | .8497 | .8505 | .8516 | .8524 | | .8556 | .8569 | .8661 | .8679 | .8705 | .8726 | .8753 | .8774 |
| TIER NO.16 | .8151 | .8341 | .8328 | .8093 | .8082 | | .8248 | .8243 | .8241 | .8240 | .8240 | .8240 | .8241 | .8245 | .8250 | .8253 | .8258 | .8267 | .8278 | .8286 | | .8320 | .8333 | .8428 | .8446 | .8473 | .8494 | .8521 | .8543 |
| TIER NO.15 | .7917 | .8105 | .8092 | .7857 | .7846 | | .8010 | .8005 | .8003 | .8002 | .8002 | .8001 | .8003 | .8007 | .8011 | .8015 | .8022 | .8030 | .8041 | .8050 | | .8084 | .8097 | .8195 | .8213 | .8241 | .8261 | .8290 | .8313 |
| TIER NO.14 | .7683 | .7871 | .7856 | .7621 | .7610 | | .7772 | .7768 | .7764 | .7764 | .7764 | .7763 | .7765 | .7769 | .7773 | .7777 | .7784 | .7792 | .7804 | .7813 | | .7848 | .7862 | .7961 | .7981 | .8009 | .8030 | .8060 | .8082 |
| TIER NO.13 | .7449 | .7636 | .7621 | .7386 | .7374 | | .7535 | .7530 | .7527 | .7527 | .7526 | .7525 | .7527 | .7531 | .7536 | .7540 | .7547 | .7555 | .7567 | .7577 | | .7613 | .7627 | .7729 | .7749 | .7777 | .7800 | .7830 | .7853 |
| TIER NO.12 | .7216 | .7402 | .7387 | .7151 | .7139 | | .7297 | .7293 | .7290 | .7289 | .7289 | .7288 | .7290 | .7293 | .7299 | .7303 | .7310 | .7319 | .7331 | .7341 | | .7378 | .7393 | .7497 | .7517 | .7547 | .7570 | .7601 | .7624 |
| TIER NO.11 | .6984 | | | .6917 | .6904 | | | | | | | | | | | | | | | | | | | | | | | | |
| TIER NO.10 | .6752 | | | | .6670 | | | | | | | | | | | | | | | | | | | | | | | | |
| TIER NO. 9 | | .7828 | .7579 | .7559 | .7548 | | .6545 | .6539 | .6536 | .6535 | .6535 | .6534 | .6536 | .6540 | .6546 | .6551 | .6559 | .6568 | .6582 | .6592 | | .6633 | .6649 | .6764 | .6785 | .7046 | .7070 | .7559 | .7812 |
| TIER NO. 8 | | .7594 | .7344 | .7324 | .7313 | | .6309 | .6303 | .6300 | .6299 | .6299 | .6298 | .6300 | .6304 | .6311 | .6315 | .6323 | .6334 | .6348 | .6358 | | .6401 | .6417 | .6534 | .6557 | .6817 | .6842 | .7330 | .7583 |
| TIER NO. 7 | | .7359 | .7110 | .7090 | .7077 | | .6073 | .6067 | .6064 | .6063 | .6063 | .6062 | .6064 | .6069 | .6075 | .6080 | .6089 | .6099 | .6113 | .6125 | | .6168 | .6185 | .6306 | .6329 | .6590 | .6615 | .7102 | .7354 |
| TIER NO. 6 | | .7126 | .6876 | .6855 | .6843 | | .5839 | .5833 | .5829 | .5828 | .5827 | .5827 | .5829 | .5834 | .5840 | .5845 | .5854 | .5865 | .5880 | .5891 | | .5936 | .5954 | .6078 | .6102 | .6363 | .6388 | .6875 | .7127 |
| TIER NO. 5 | | | .6644 | .6622 | .6609 | | .5604 | .5598 | .5594 | .5594 | .5593 | .5592 | .5594 | .5599 | .5606 | .5612 | .5620 | .5632 | .5647 | .5659 | | .5706 | .5723 | .5852 | .5876 | .6136 | .6162 | .6649 | .6901 |
| TIER NO. 4 | | | | | | | .5370 | .5364 | .5360 | .5359 | .5358 | .5358 | .5360 | .5365 | .5373 | .5378 | .5387 | .5399 | .5415 | .5427 | | .5475 | .5494 | .5626 | .5651 | .5912 | .5939 | .6423 | |
| TIER NO. 3 | | | | | | | .5138 | .5131 | .5127 | .5126 | .5125 | .5125 | .5127 | .5132 | .5139 | .5145 | .5155 | .5167 | .5184 | .5196 | | .5246 | .5265 | .5402 | .5427 | .5688 | .5715 | | |
| TIER NO. 2 | | | | | | | .4905 | .4899 | .4894 | .4893 | .4893 | .4892 | .4894 | .4900 | .4908 | .4913 | .4923 | .4936 | .4953 | .4967 | | .5018 | .5038 | .5179 | .5205 | .5465 | .5493 | | |
| TIER NO. 1 | | | | | | | .4674 | .4667 | .4662 | .4661 | .4661 | .4660 | .4662 | .4668 | .4676 | .4682 | .4693 | .4705 | .4724 | .4737 | | .4791 | .4811 | .4957 | .4984 | | | | |

APPROXIMATION FORMULA AY - .43560 + .009073*Z + .11429*( X /299.5M - .35272 ) **2

Figure 5.16. Lateral accelerations for 7 m GM

### *5.3.2.1. Comparison for Different Metacentric Heights*

The maximum accelerations for three different longitudinal positions for different GMs are represented in Table 5.3. The values selected are for three bays that includes aft bay 67, mid bay 33 and fore bay 3. Figure 5.17 shows the graph for comparison of accelerations for the selected bays at tier number 20.

Table 5.3. Maximum accelerations for maximum service speed and different metacentric heights

| | Maximum Accelerations (x G) | | |
|---|---|---|---|
| GM (m) | Aft Bay (67) | Mid Bay (33) | Fore Bay (3) |
| 1 | 0.3435 | 0.3314 | 0.3535 |
| 2 | 0.4646 | 0.4537 | 0.4708 |
| 3.16 | 0.5811 | 0.5713 | 0.5805 |

| | | | |
|---|---|---|---|
| 4.5 | 0.7366 | 0.7277 | 0.726 |
| 5.5 | 0.8369 | 0.8286 | 0.8183 |
| 7 | 0.976 | 0.9684 | 0.945 |

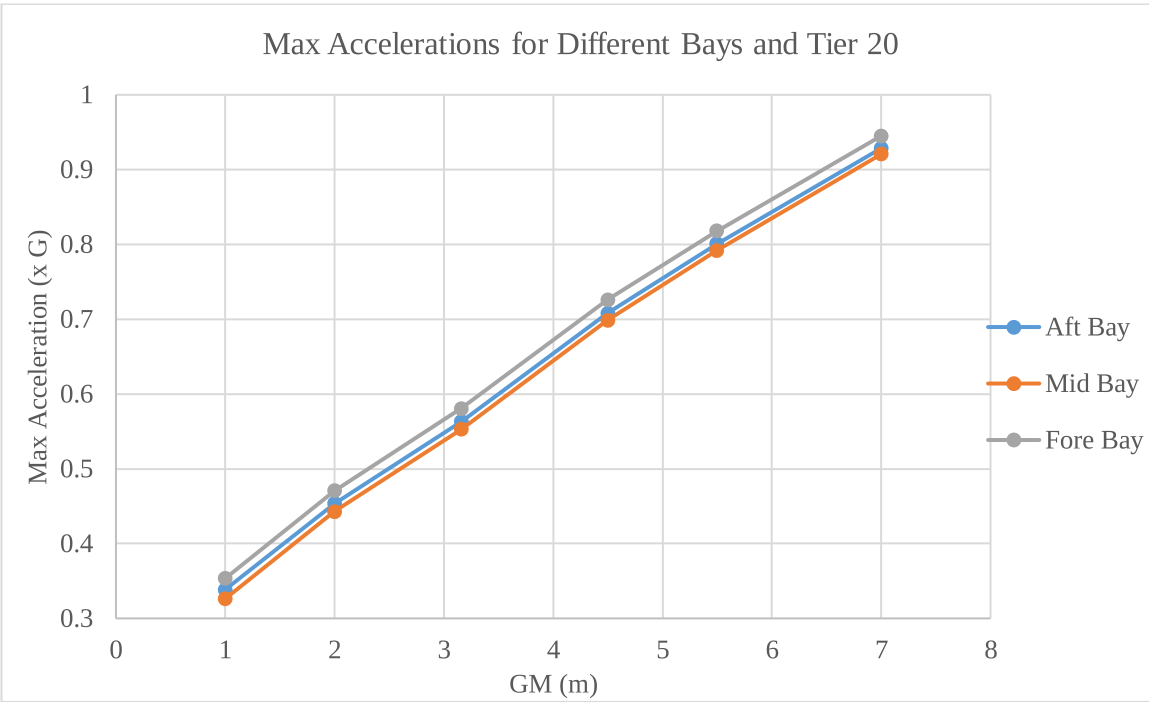



Figure 5.17. Comparison of accelerations for different longitudinal positions at tier no. 20

## 5.4. Ship 4 – 20,000 TEU

This is the largest ship included in the analysis with an overall length of around 400 m. Figure 5.18 shows the ship hull lines for 20 frames.

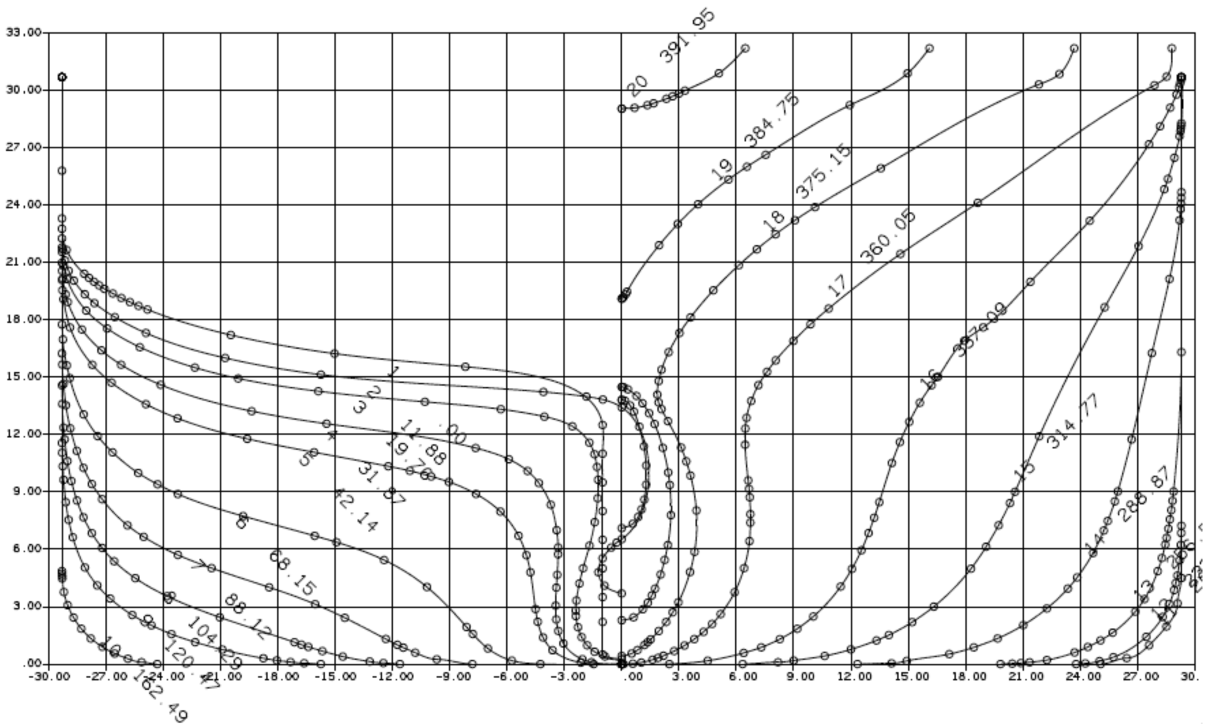



Figure 5.18. Ship 4 hull lines for 20 frames

### *5.4.1. Maximum Roll Angle and Roll Axis*

Figures 5.19 and 5.20 shows the maximum roll angle and height of roll axis from keel base, respectively. Since this is a very large ship, the associated maximum roll angles at even high GMs are smaller as compared to the previous ships.

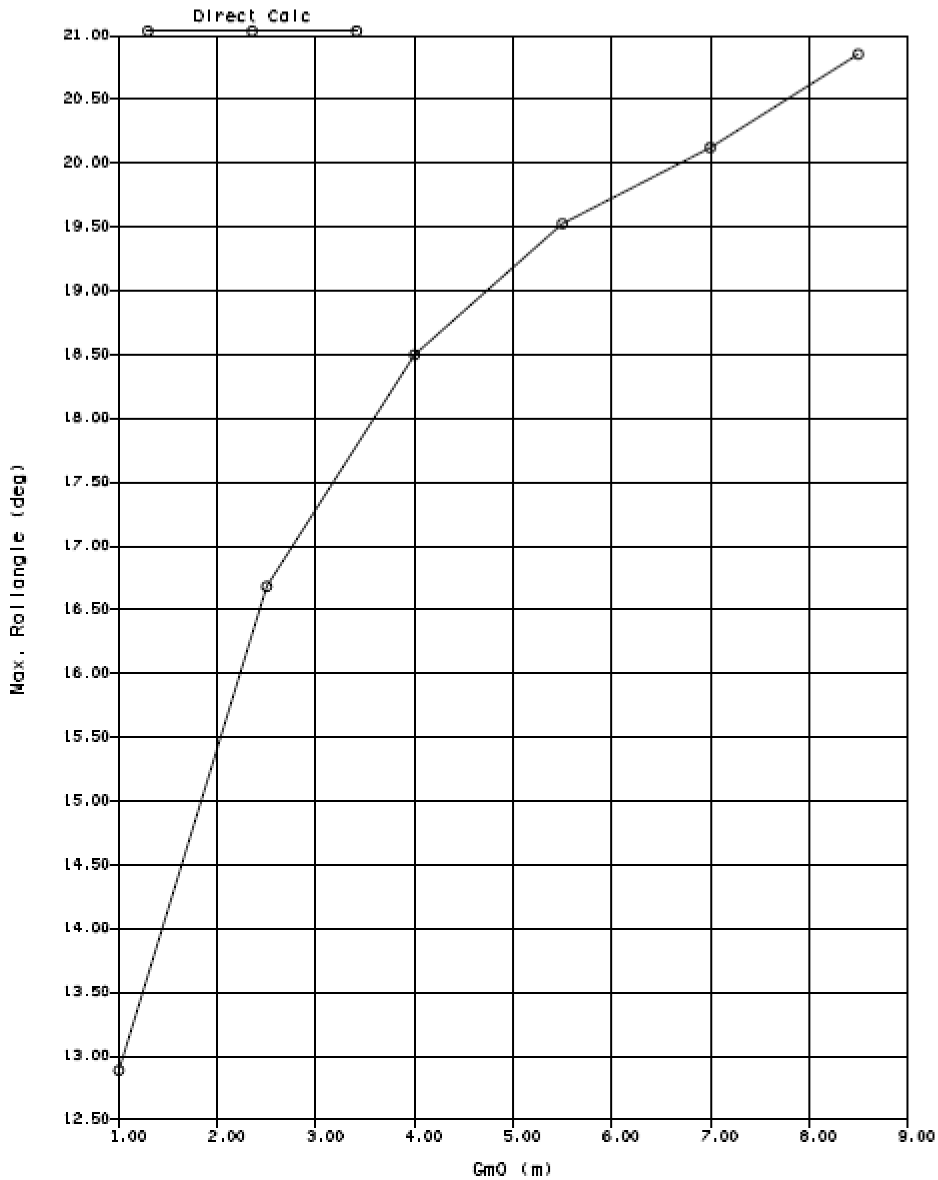



Figure 5.19. Max roll angle over a range of GM

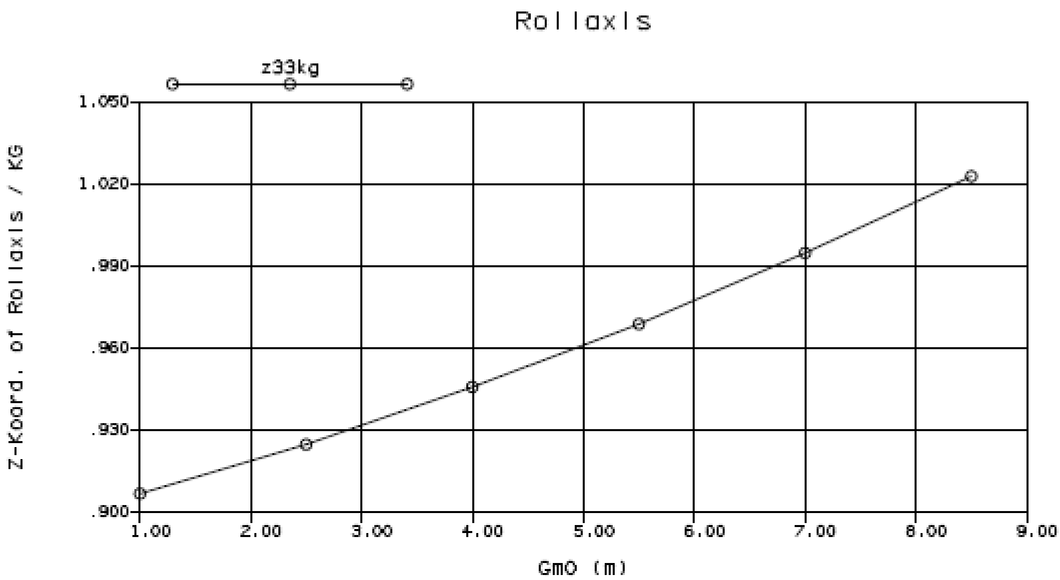



Figure 5.20. Height of roll axis above base

### *5.4.2. Lateral Accelerations*

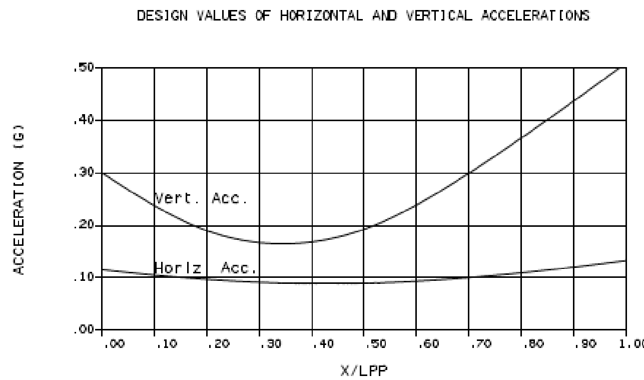
Figure 5.21 shows the table with the values of lateral accelerations for the highest considered GM of 8.5 m. The figure also displays the vertical and horizontal accelerations distributed over the ship's length.

LATERAL ACCELERATION CALCULATION

CONTAINER VESSEL 20119 TEU-CLASS
CONTAINERS ON DECK AND IN HOLDS

DRAUGHT - 14.00 M
METACENTRIC HEIGHT GMO = 8.50 M
ROLL PERIOD Troll - 15.16 S

DESIGN VALUES:
HORIZONTAL ACCELERATION ) SEE
VERTICAL ACCELERATION ) FIG.
ROLL ANGLE - 20.9 DEG




CALCULATED LATERAL ACCELERATIONS IN G

| | BAY 94 HLD10A | BAY 91 HLD10A | BAY 89 HLD10A | BAY 87 HLD10A | BAY 85 HLD10A | ENGINE FUNNEL | BAY 63 HLD10A | BAY 61 HLD10A | BAY 59 HOLD9F | BAY 57 HOLD8A | BAY 55 HOLD8A | BAY 53 HOLD8F |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| X (M) | 1.64 | 12.63 | 18.96 | 27.38 | 33.51 | 43.00 | 127.28 | 133.41 | 141.83 | 147.96 | 156.38 | 162.51 |
| TIER NO.23 | | .7519 | .7513 | .7504 | .7498 | | .7452 | .7452 | .7451 | .7451 | .7450 | .7451 |
| TIER NO.22 | .7187 | .7357 | .7350 | .7342 | .7336 | | .7289 | .7289 | .7288 | .7288 | .7287 | .7287 |
| TIER NO.21 | .7026 | .7196 | .7188 | .7180 | .7174 | | .7126 | .7125 | .7125 | .7124 | .7124 | .7124 |
| TIER NO.20 | .6865 | .7033 | .7027 | .7018 | .7012 | | .6962 | .6962 | .6961 | .6961 | .6960 | .6961 |
| TIER NO.19 | .6704 | .6872 | .6865 | .6856 | .6849 | | .6799 | .6798 | .6798 | .6798 | .6797 | .6797 |
| TIER NO.18 | .6543 | .6711 | .6704 | .6694 | .6687 | | .6636 | .6635 | .6635 | .6634 | .6634 | .6634 |
| TIER NO.17 | .6383 | .6549 | .6542 | .6533 | .6526 | | .6473 | .6473 | .6472 | .6472 | .6471 | .6471 |
| TIER NO.16 | .6222 | .6389 | .6381 | .6372 | .6365 | | .6311 | .6310 | .6309 | .6309 | .6308 | .6309 |
| TIER NO.15 | .6062 | .6228 | .6220 | .6210 | .6203 | | .6148 | .6147 | .6147 | .6146 | .6146 | .6146 |
| TIER NO.14 | .5902 | .6067 | .6060 | .6049 | .6042 | | .5985 | .5985 | .5984 | .5984 | .5983 | .5984 |
| TIER NO.13 | .5743 | .5907 | .5899 | .5889 | .5881 | | .5823 | .5822 | .5822 | .5821 | .5821 | .5821 |
| TIER NO.12 | .5583 | | | | | | | | | | | |
| TIER NO.11 | | .6379 | .6371 | .6039 | .6032 | | .5488 | .5487 | .5487 | .5486 | .5485 | .5486 |
| TIER NO.10 | | .6218 | .6210 | .5879 | .5871 | | .5326 | .5325 | .5325 | .5324 | .5324 | .5324 |
| TIER NO. 9 | | .6058 | .6050 | .5718 | .5711 | | .5164 | .5164 | .5163 | .5163 | .5162 | .5162 |
| TIER NO. 8 | | .5897 | .5889 | .5558 | .5550 | | .5003 | .5002 | .5002 | .5001 | .5000 | .5001 |
| TIER NO. 7 | | .5737 | .5729 | .5398 | .5390 | | .4842 | .4841 | .4840 | .4840 | .4839 | .4839 |
| TIER NO. 6 | | .5577 | .5569 | .5238 | .5230 | | .4681 | .4680 | .4679 | .4679 | .4678 | .4678 |
| TIER NO. 5 | | | | .5079 | .5071 | | .4520 | .4519 | .4518 | .4518 | .4517 | .4517 |
| TIER NO. 4 | | | | .4920 | .4912 | | .4360 | .4359 | .4358 | .4358 | .4357 | .4357 |
| TIER NO. 3 | | | | | | | .4200 | .4199 | .4198 | .4198 | .4197 | .4197 |
| TIER NO. 2 | | | | | | | .4040 | .4040 | .4039 | .4038 | .4037 | .4037 |
| TIER NO. 1 | | | | | | | .3881 | .3880 | .3879 | .3879 | .3878 | .3878 |

| | BAY 51 HOLD7A | BAY 49 HOLD7F | BAY 47 HOLD6A | BAY 45 HOLD6F | BAY 43 HOLD5A | BAY 41 HOLD5F | DECK - HOUSE | BAY 31 HOLD5A | BAY 29 HOLD5F | BAY 27 HOLD4A | BAY 25 HOLD4F | BAY 09 HOLD2A | BAY 07 HOLD2F | BAY 05 HOLD3F | BAY 03 HOLD2F | BAY 01 HOLD3F |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| X (M) | 170.93 | 177.06 | 185.48 | 191.61 | 200.03 | 206.16 | 181.00 | 255.73 | 261.86 | 270.28 | 276.41 | 334.61 | 343.03 | 349.16 | 357.58 | 363.71 |
| TIER NO.23 | .7452 | .7453 | .7455 | .7456 | .7458 | .7461 | | .7492 | .7497 | .7505 | .7510 | | | | | |
| TIER NO.22 | .7289 | .7290 | .7292 | .7293 | .7295 | .7298 | | .7329 | .7335 | .7342 | .7348 | | | | | |
| TIER NO.21 | .7126 | .7127 | .7129 | .7130 | .7132 | .7135 | | .7167 | .7172 | .7180 | .7186 | .7260 | .7273 | .7282 | | |
| TIER NO.20 | .6962 | .6964 | .6966 | .6967 | .6969 | .6972 | | .7004 | .7010 | .7018 | .7024 | .7099 | .7113 | .7122 | .7136 | .7146 |
| TIER NO.19 | .6799 | .6801 | .6803 | .6804 | .6806 | .6809 | | .6843 | .6848 | .6857 | .6862 | .6939 | .6953 | .6963 | .6977 | .6987 |
| TIER NO.18 | .6636 | .6638 | .6639 | .6641 | .6643 | .6646 | | .6681 | .6687 | .6695 | .6701 | .6780 | .6793 | .6803 | .6818 | .6829 |
| TIER NO.17 | .6473 | .6475 | .6477 | .6478 | .6480 | .6483 | | .6519 | .6525 | .6533 | .6540 | .6620 | .6634 | .6644 | .6659 | .6670 |
| TIER NO.16 | .6311 | .6312 | .6314 | .6315 | .6317 | .6321 | | .6357 | .6363 | .6372 | .6378 | .6461 | .6475 | .6485 | .6500 | .6511 |
| TIER NO.15 | .6148 | .6149 | .6151 | .6153 | .6155 | .6159 | | .6196 | .6202 | .6211 | .6217 | .6301 | .6316 | .6327 | .6342 | .6353 |
| TIER NO.14 | .5985 | .5987 | .5989 | .5990 | .5993 | .5997 | | .6034 | .6041 | .6050 | .6058 | .6142 | .6157 | .6168 | .6184 | .6196 |
| TIER NO.13 | .5823 | .5824 | .5827 | .5828 | .5831 | .5834 | | .5873 | .5880 | .5889 | .5896 | .5984 | .5999 | .6010 | .6026 | .6038 |
| TIER NO.12 | | | | | | | | | | | | | | | | |
| TIER NO.11 | .5488 | .5490 | .5492 | .5494 | .5496 | .5500 | | .5541 | .5548 | .5558 | .5565 | .5657 | .5673 | .5685 | .6332 | .6343 |
| TIER NO.10 | .5326 | .5328 | .5330 | .5332 | .5334 | .5338 | | .5380 | .5388 | .5398 | .5405 | .5500 | .5516 | .5528 | .6174 | .6186 |
| TIER NO. 9 | .5165 | .5166 | .5169 | .5170 | .5173 | .5177 | | .5220 | .5228 | .5238 | .5246 | .5343 | .5359 | .5372 | .6016 | .6029 |
| TIER NO. 8 | .5003 | .5005 | .5007 | .5009 | .5012 | .5016 | | .5061 | .5068 | .5079 | .5087 | .5186 | .5203 | .5216 | .5859 | .5871 |
| TIER NO. 7 | .4842 | .4843 | .4846 | .4848 | .4851 | .4855 | | .4901 | .4909 | .4920 | .4928 | .5030 | .5047 | .5060 | .5702 | .5715 |
| TIER NO. 6 | .4681 | .4683 | .4685 | .4687 | .4690 | .4695 | | .4742 | .4750 | .4761 | .4769 | .4874 | .4892 | .4905 | .5546 | .5559 |
| TIER NO. 5 | .4520 | .4522 | .4525 | .4527 | .4529 | .4534 | | .4583 | .4592 | .4603 | .4612 | .4719 | .4737 | .4751 | .5390 | .5403 |
| TIER NO. 4 | .4360 | .4362 | .4365 | .4367 | .4370 | .4375 | | .4425 | .4433 | .4445 | .4454 | .4564 | .4583 | .4597 | | |
| TIER NO. 3 | .4200 | .4202 | .4205 | .4207 | .4210 | .4215 | | .4267 | .4276 | .4288 | .4297 | .4410 | .4429 | .4444 | | |
| TIER NO. 2 | .4040 | .4042 | .4045 | .4048 | .4051 | .4056 | | .4110 | .4119 | .4131 | .4141 | .4257 | .4277 | .4291 | | |
| TIER NO. 1 | .3881 | .3884 | .3887 | .3889 | .3892 | .3898 | | .3953 | .3962 | .3975 | .3985 | .4105 | .4125 | .4139 | | |

APPROXIMATION FORMULA AY - .36476 + .006210*Z + .07583*( X /399.8M - .36645 ) **2

Figure 5.21. Lateral accelerations for 8.5 m GM

### *5.4.2.1. Comparison for Different Metacentric Heights*

The maximum lateral accelerations for different metacentric heights are shown in Table 5.4. The accelerations are selected for three different longitudinal positions including bay 91 for aft part, bay 47 for mid ship and bay 3 for fore part of the ship. Figure 5.22 show the graph for the comparison of accelerations for the selected bays at tier no. 20 for given GM.

Table 5.4. Maximum accelerations for maximum service speed and different metacentric heights

| | Maximum Accelerations (x G) | | |
|---|---|---|---|
| GM (m) | Aft Bay (91) | Mid Bay (47) | Fore Bay (3) |
| 1 | 0.2938 | 0.2836 | 0.2997 |
| 2.5 | 0.414 | 0.405 | 0.4131 |
| 4 | 0.5081 | 0.5 | 0.4986 |

| | | | |
|---|---|---|---|
| 5.5 | 0.5913 | 0.5838 | 0.5725 |
| 7 | 0.6673 | 0.6605 | 0.6392 |
| 8.5 | 0.7519 | 0.7455 | 0.7136 |

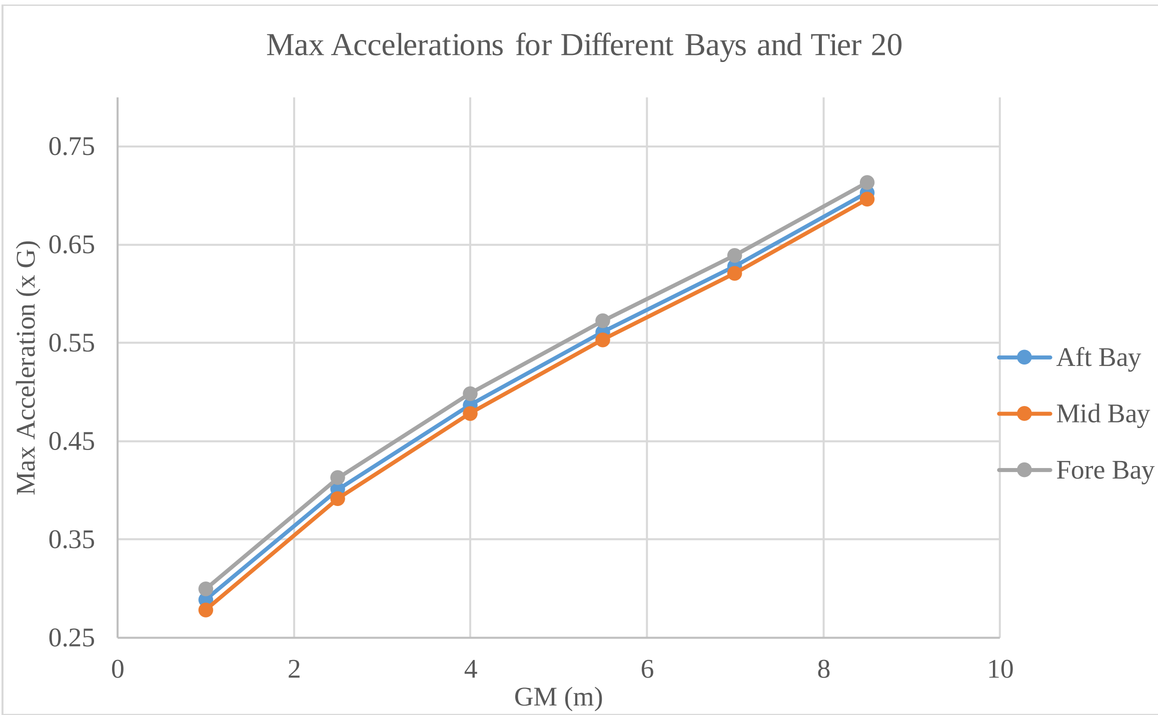



Figure 5.22. Comparison of accelerations for different longitudinal positions at tier no. 20

## 5.5. Ship 5 – 1100 TEU

This ship is one of the two small sized vessels considered in the analysis. Figure 5.23 shows the ship hull lines for 20 selected frames.

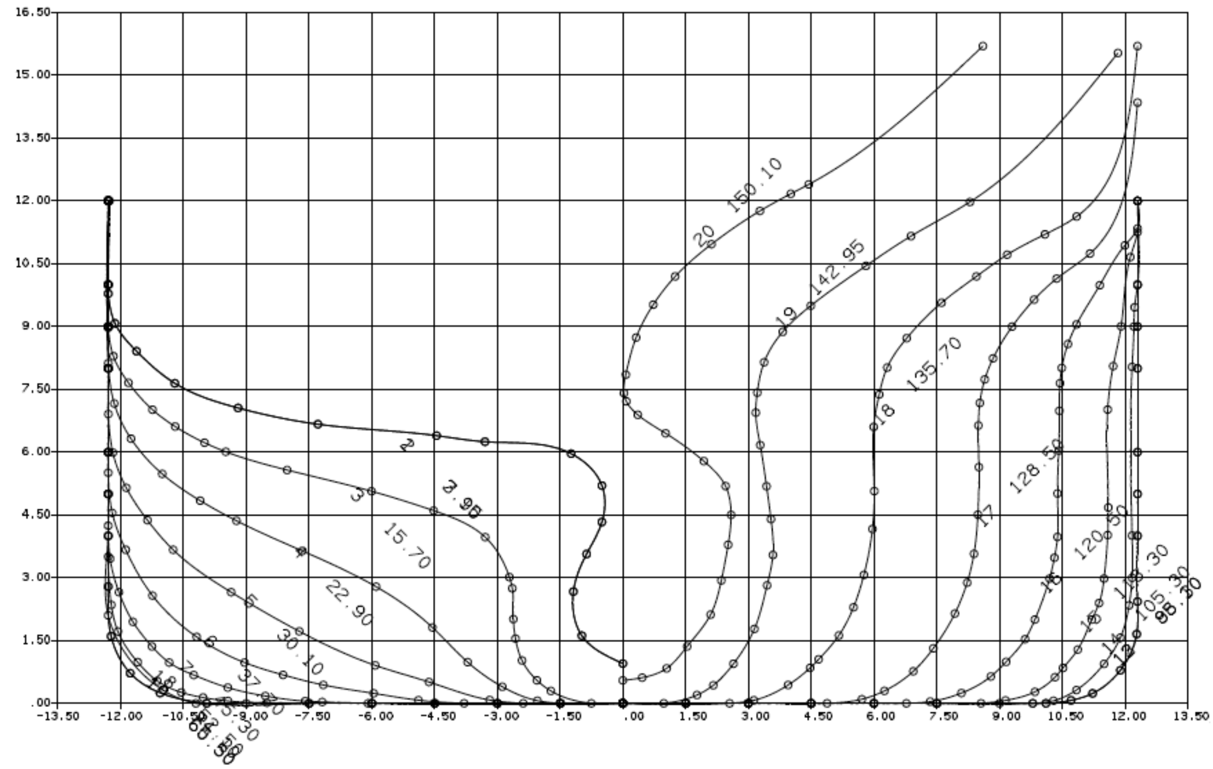



Figure 5.23. Ship 5 hull lines for 20 frames

### *5.5.1. Maximum Roll Angle and Roll Axis*

Figure 5.24 illustrates the maximum roll angle and Figure 5.25 show the vertical height of the roll axis above keel base over different GMs ranging from low to high.

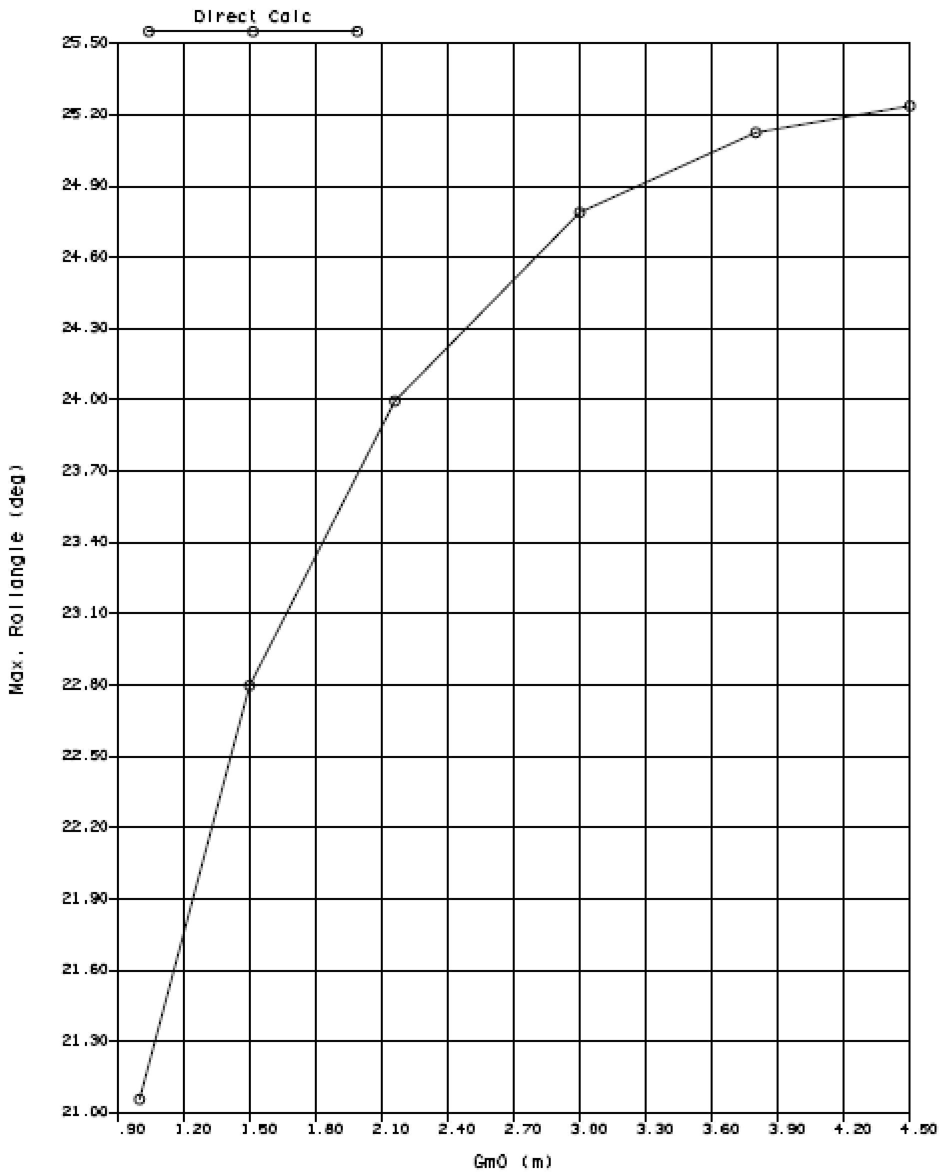



Figure 5.24. Max roll angle over a range of GM

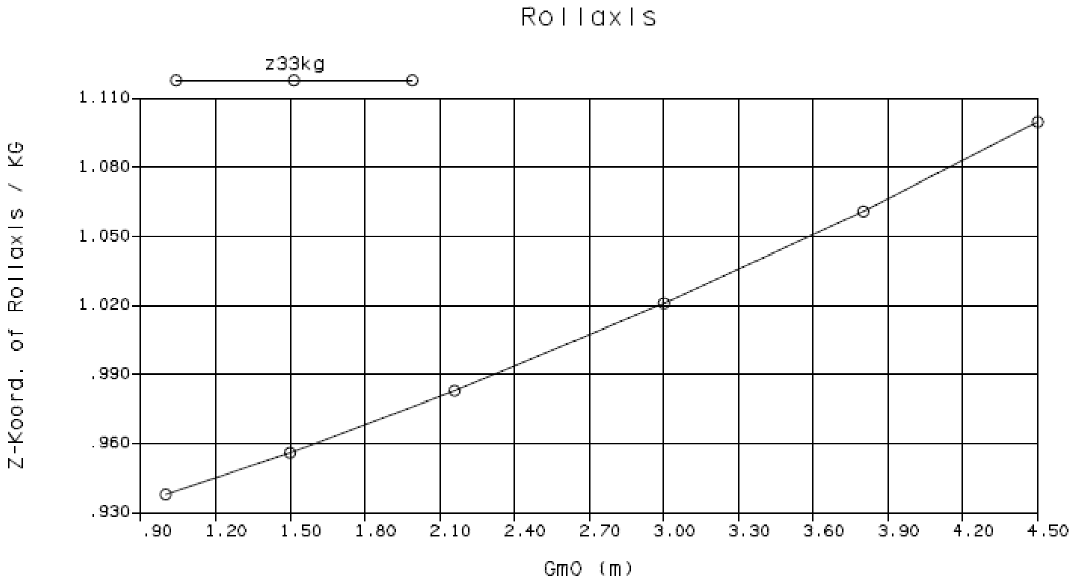



Figure 5.25. Height of roll axis above keel base

From Figure 5.24, it can be seen that the amount of increment in the maximum roll angle with the increasing GM becomes smaller after GM of 3 m and for higher GM, the maximum roll angle rises with little difference comparatively. This phenomena can be seen for ship 1 (1900 TEU) also where the max roll angle value becomes stable near GM of 4m.

### *5.5.2. Lateral Accelerations*

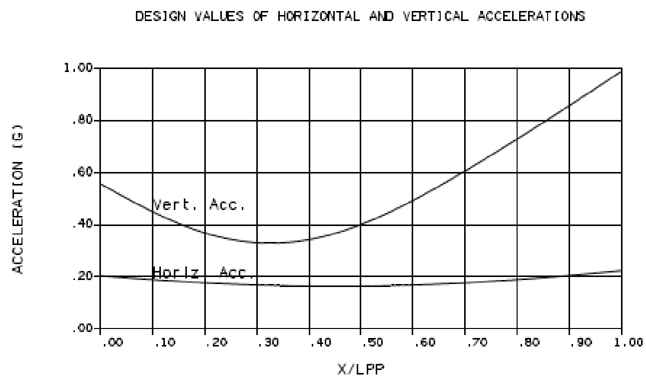
In Figure 5.26, the values for the lateral accelerations are displayed for the highest considered GM of 4.5 m. This is a smaller vessel as compared to the vessels analyzed above therefore it has higher maximum roll angle values (Figure 5.24) and greater vertical and horizontal accelerations.

LATERAL ACCELERATION CALCULATION

CONTAINER VESSEL 3800 TEU-CLASS
CONTAINERS ON DECK AND IN HOLDS

DRAUGHT - 6.00 M
METACENTRIC HEIGHT GMO = 4.50 M
ROLL PERIOD Troll - 8.80 S

DESIGN VALUES:
HORIZONTAL ACCELERATION ) SEE
VERTICAL ACCELERATION ) FIG.
ROLL ANGLE - 25.2 DEG




CALCULATED LATERAL ACCELERATIONS IN G

| | BAY 33 HOLD6A | BAY 31 HOLD6F | BAY 29 HOLD5A | BAY 27 HOLD5F | BAY 25 HOLD4A | BAY 23 HOLD4F | BAY 21 HOLD6A | BAY 19 HOLD6F | BAY 17 HOLD5A | BAY 15 HOLD5F | BAY 13 HOLD4A | BAY 11 HOLD4F | BAY 09 HOLD3A | BAY 07 HOLD3F | BAY 05 HOLD2A | BAY 03 HOLD2F | BAY 01 HOLD3F |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| X (M) | 15.88 | 22.01 | 29.36 | 37.42 | 45.13 | 52.57 | 60.33 | 67.87 | 75.53 | 83.07 | 90.73 | 98.27 | 105.93 | 113.47 | 121.13 | 128.67 | 136.33 |
| TIER NO.10 | .9982 | .9950 | .9914 | | | | | | | | | | | | | | |
| TIER NO. 9 | .9410 | .9377 | .9338 | .9416 | .9397 | .9397 | .9398 | .9418 | .9439 | .9477 | .9520 | | | | | | |
| TIER NO. 8 | .8840 | .8804 | .8765 | .8841 | .8821 | .8821 | .8822 | .8842 | .8864 | .8905 | .8950 | .9011 | .9078 | .9156 | .9239 | | .9389 |
| TIER NO. 7 | .8274 | .8236 | .8193 | .8267 | .8246 | .8246 | .8247 | .8269 | .8293 | .8336 | .8384 | .8448 | .8518 | .8599 | .8686 | .8782 | .8844 |
| TIER NO. 6 | .7710 | .7671 | .7625 | .7697 | .7675 | .7675 | .7676 | .7698 | .7723 | .7769 | .7819 | .7887 | .7961 | .8046 | .8137 | .8237 | |
| TIER NO. 5 | .7152 | .7109 | .7061 | | | | | | | | | | | | | | .7975 |
| TIER NO. 4 | | | | .6743 | .6718 | .6718 | .6718 | .6744 | .6772 | .6823 | .6878 | .6952 | .7032 | .7125 | .7223 | .7331 | .7444 |
| TIER NO. 3 | | | | .6184 | .6157 | .6156 | .6157 | .6184 | .6214 | .6268 | .6327 | .6405 | .6490 | .6587 | .6690 | .6802 | .6919 |
| TIER NO. 2 | | | | .5631 | .5601 | .5601 | .5602 | .5631 | .5662 | .5720 | .5782 | .5865 | .5954 | .6056 | .6163 | .6280 | .6402 |
| TIER NO. 1 | | | | .5085 | .5054 | .5053 | .5054 | .5084 | .5118 | .5180 | .5246 | .5333 | .5427 | .5534 | .5646 | .5767 | .5894 |

APPROXIMATION FORMULA AY - .45097 + .021498*Z + .23671*( X /150.6M - .34953 ) **2

Figure 5.26. Lateral accelerations for 4.5 m GM

### *5.5.2.1. Comparison for Different Metacentric Heights*

The maximum lateral accelerations for three different longitudinal positions, which occurs on the top most tiers of the selected bays are represented in Table 5.5. The longitudinal positions include bay number 33 in aft part, bay number 17 in mid ship and bay number 1 in fore part of the ship.

Table 5.5. Maximum accelerations for maximum service speed and different metacentric heights

| | Maximum Accelerations (x G) | | |
|---|---|---|---|
| GM (m) | Aft Bay (33) | Mid Bay (17) | Fore Bay (1) |
| 1 | 0.531 | 0.513 | 0.5652 |
| 1.5 | 0.616 | 0.5929 | 0.6395 |
| 2.16 | 0.7114 | 0.6814 | 0.7178 |

| | | | |
|---|---|---|---|
| 3 | 0.8215 | 0.7827 | 0.8046 |
| 3.8 | 0.9182 | 0.871 | 0.8785 |
| 4.5 | 0.9982 | 0.9439 | 0.9389 |

In the Figure 5.27, the comparison of accelerations for each selected bay and at tier number 8 is performed showing an increasing trend of acceleration values with the increase in GM.

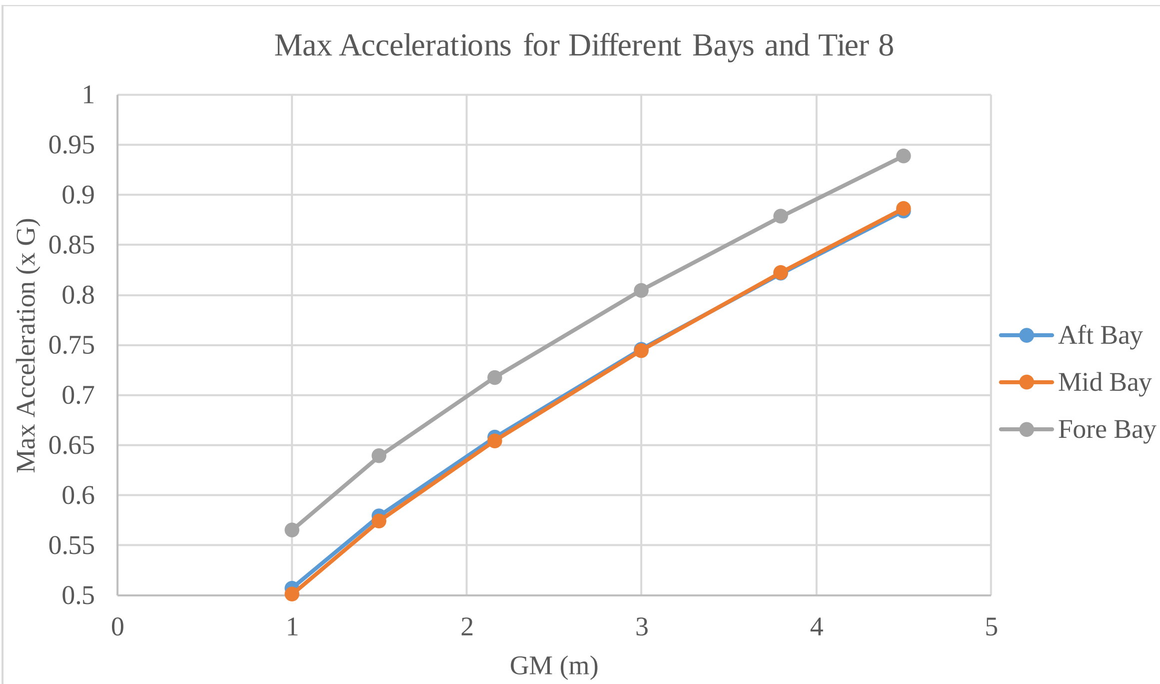



Figure 5.27. Comparison of accelerations for different longitudinal positions at tier no. 8

## 5.6. Ship 6 – 47 TEU

This is the smallest ship considered in the analysis with an overall length of around 67 m. Figure 5.28 displays the ship hull lines for 20 frames across the ship's length.

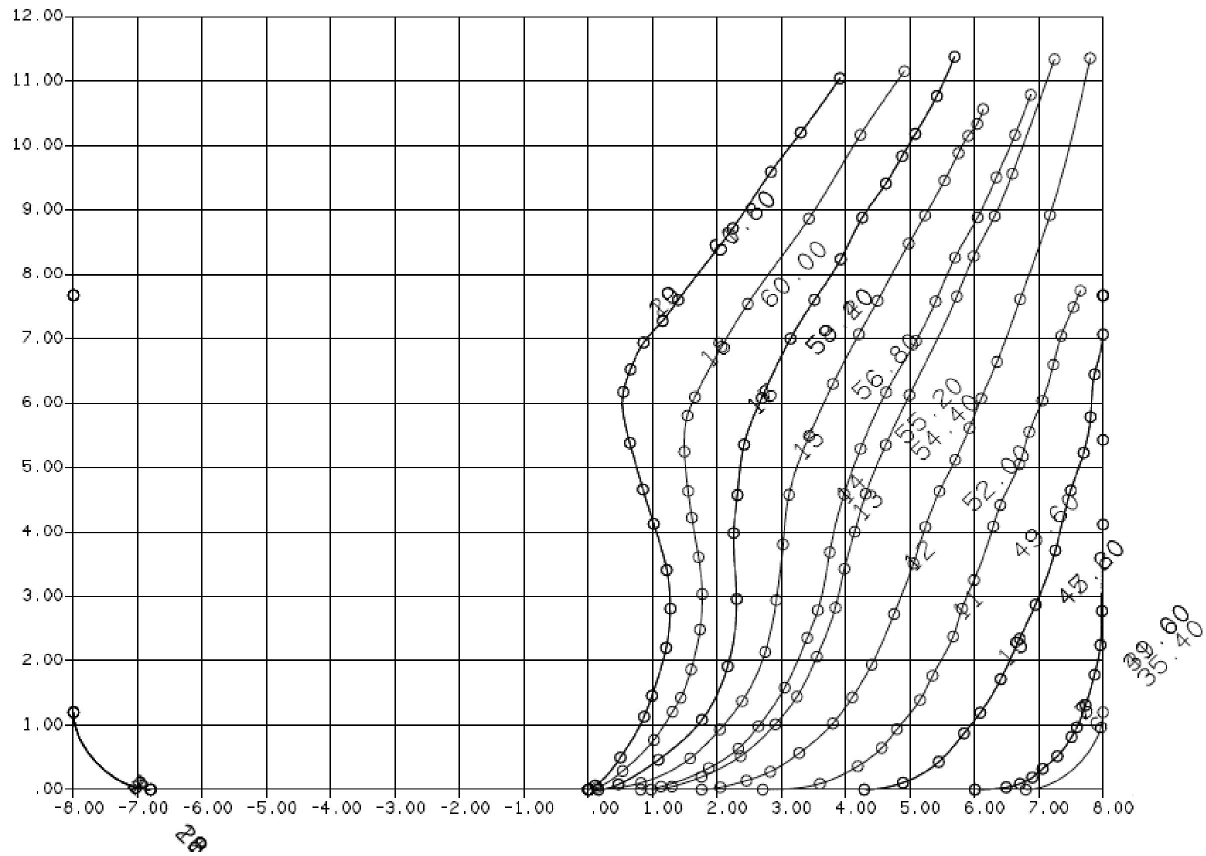


Figure 5.28. Ship 6 hull lines for 20 frames

### *5.6.1. Maximum Roll Angle and Roll Axis*

As compared to the previous five ships, the maximum roll angle values are the highest for this ship as represented in Figure 5.29. It is also observed that the slope of the increasing curve of roll angle does not reduce significantly for higher GM and the maximum roll angle values are getting higher as the metacentric height is increased. Here, the formulation has been done for a maximum GM of 4 m.

Figure 5.30 shows the height of the roll axis above the keel base.

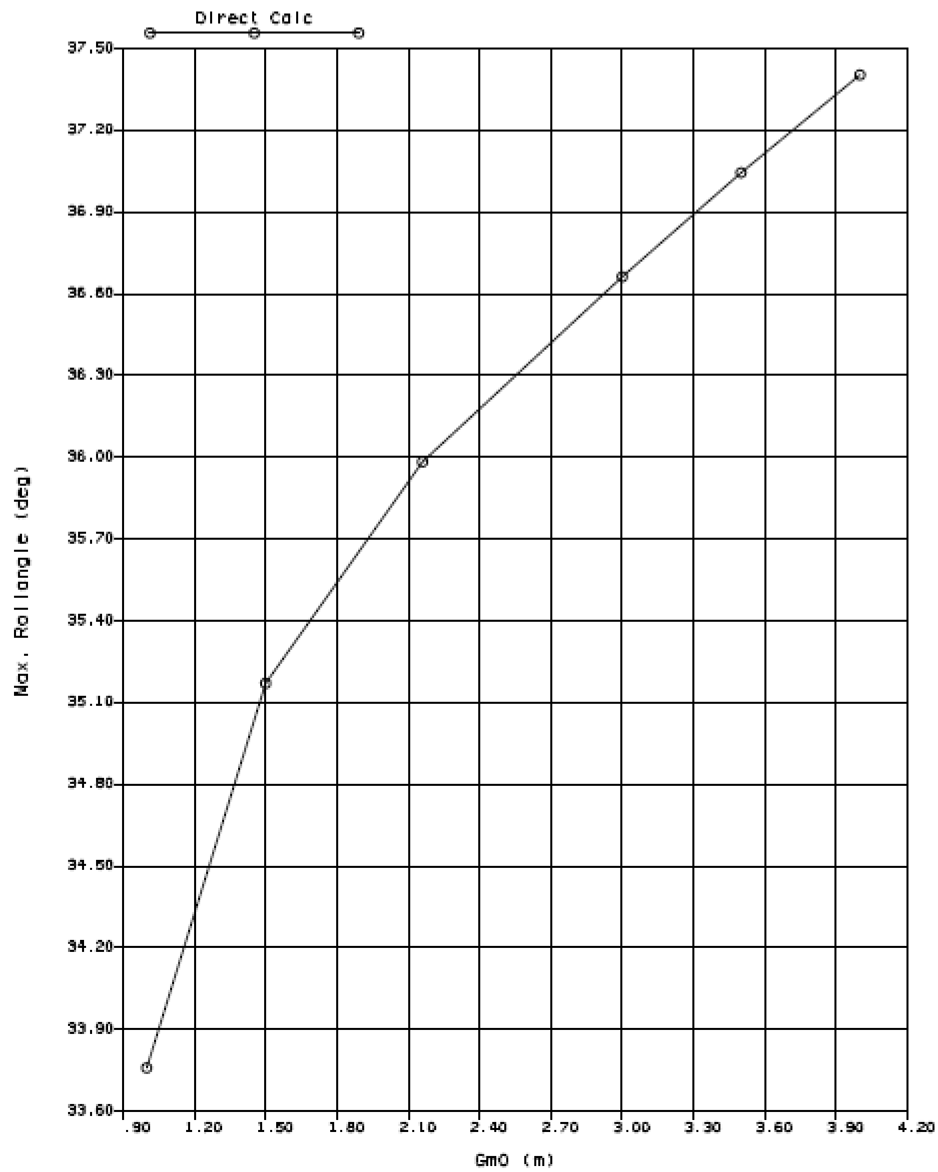



Figure 5.29. Max roll angle over a range of GM

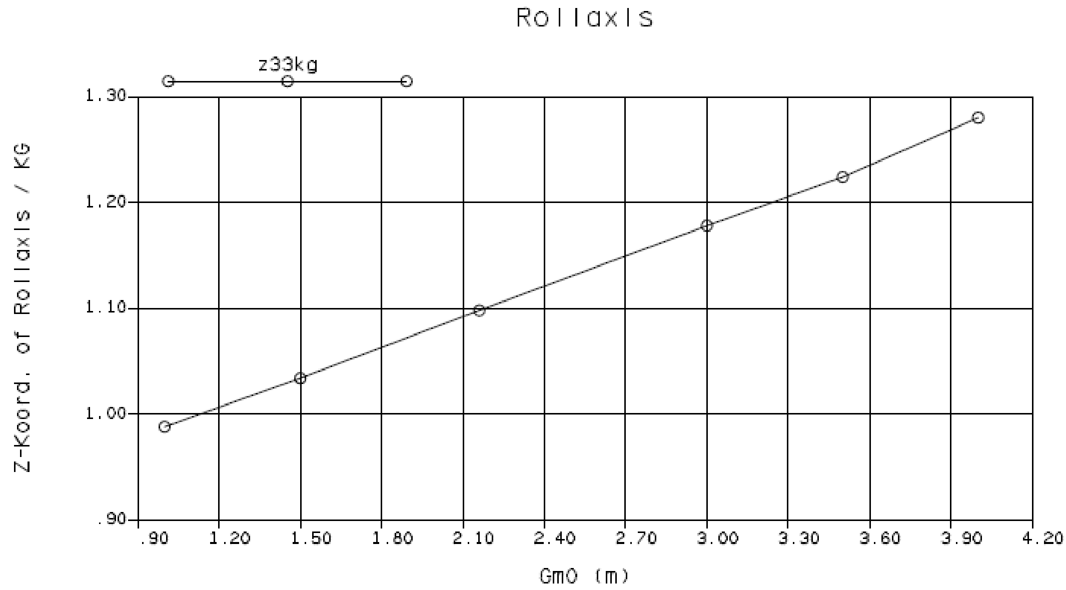



Figure 5.30. Height of roll axis above keel base

### *5.6.2. Lateral Accelerations*

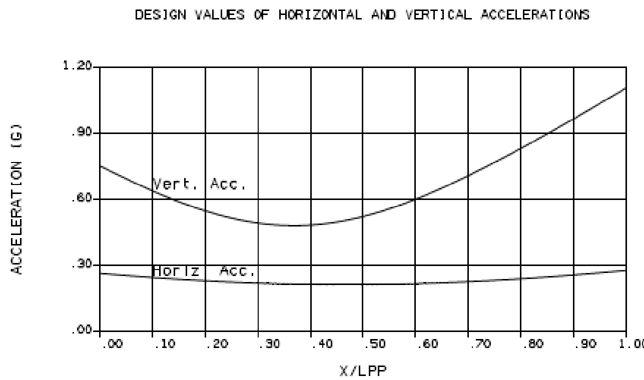
The lateral accelerations have been formulated by QUERROLL for six defined metacentric heights from 1 m to 4 m. Figure 5.31 shows the accelerations for the highest considered GM of 4 m. The image showing vertical and horizontal acceleration distribution over the ship's length displays the highest vertical accelerations as compared to all the previously described ships.

LATERAL ACCELERATION CALCULATION

CONTAINER VESSEL 47 TEU-CLASS
CONTAINERS ON DECK AND IN HOLDS

DRAUGHT - 5.70 M
METACENTRIC HEIGHT GMO = 4.00 M
ROLL PERIOD Troll - 6.12 S

DESIGN VALUES:
HORIZONTAL ACCELERATION ) SEE
VERTICAL ACCELERATION ) FIG.
ROLL ANGLE - 37.4 DEG




CALCULATED LATERAL ACCELERATIONS IN G

| | BAY 09 HOLD3A | BAY 07 HOLD3F | BAY 05 HOLD2A | MACHINERY | BAY 03 HOLD2F | BAY 01 HOLD3F |
|---|---|---|---|---|---|---|
| X (M) | 9.60 | 15.40 | 21.70 | 28.00 | 36.00 | 42.40 |
| TIER NO. 5 | | | | | 1.3990 | 1.4156 |
| TIER NO. 4 | 1.2097 | 1.2170 | 1.2112 | | 1.2253 | 1.2436 |
| TIER NO. 3 | 1.0392 | 1.0446 | 1.0380 | | 1.0538 | 1.0743 |
| TIER NO. 2 | | | | | | |
| TIER NO. 1 | | .6854 | .6764 | | .6969 | |

APPROXIMATION FORMULA AY - .61198 + .065101*Z + .36655*( X / 62.4M - .37010 ) **2

Figure 5.31. Lateral accelerations for 4 m GM

#### *5.6.2.1. Comparison for Different Metacentric Heights*

The maximum lateral accelerations for three different longitudinal bays, occurring at the top most tier of that particular stack, have been represented in the Table 5.6. The selected bays at three different positions are bay number 9 at aft part, bay number 5 at mid ship and bay number 1 at fore part of the ship.

Table 5.6. Maximum accelerations for maximum service speed and different metacentric heights

| | Maximum Accelerations (x G) | | |
|---|---|---|---|
| GM (m) | Aft Bay (9) | Mid Bay (5) | Fore Bay (1) |
| 1 | 0.784 | 0.768 | 0.8484 |
| 1.5 | 0.8687 | 0.8553 | 0.9564 |
| 2.16 | 0.9615 | 0.952 | 1.0795 |

| | | | |
|---|---|---|---|
| 3 | 1.0745 | 1.07 | 1.2317 |
| 3.5 | 1.1423 | 1.1408 | 1.3236 |
| 4 | 1.2097 | 1.2112 | 1.4156 |

The graph displayed in Figure 5.32 shows the comparison of the lateral accelerations for all three selected bays and at tier number 4. The graph indicates that at the bow, the accelerations are always higher from low to high GM, as compared to the other parts of the ship.

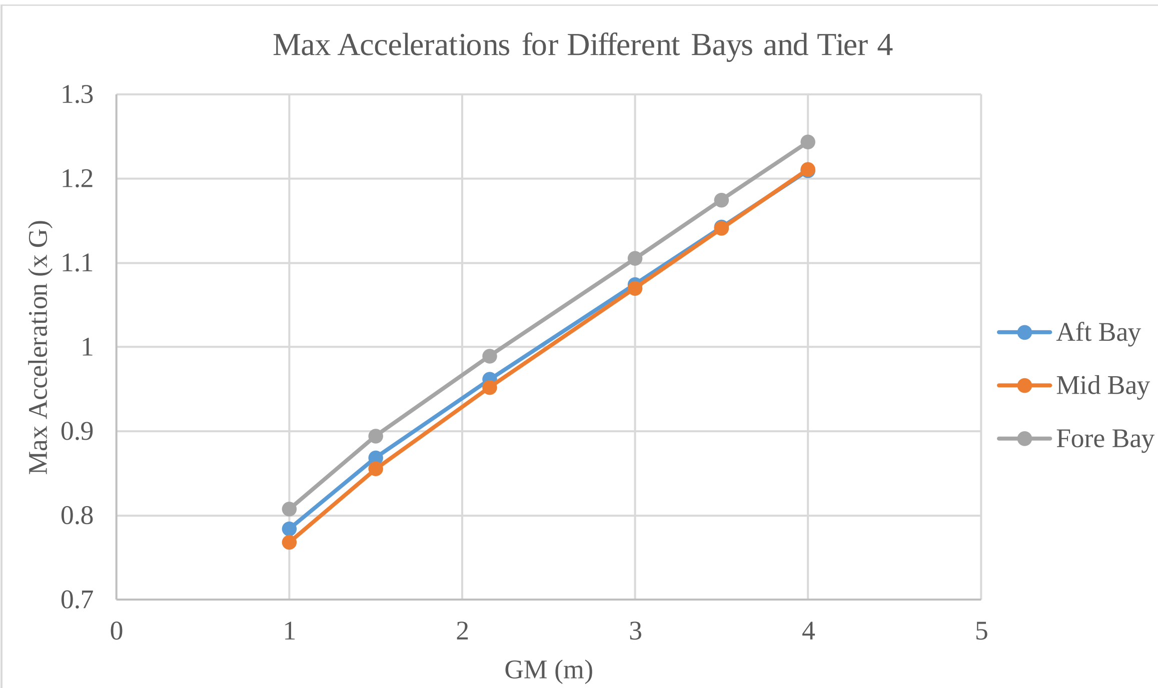



Figure 5.32. Comparison of accelerations for different longitudinal positions at tier no. 4

## 5.7. Maximum Acceleration Comparison for Different Ships

A comparison is made for the increase in maximum lateral acceleration from GM 1 m to 4 m in Figure 5.33. Since the ship observes maximum accelerations in the bow, therefore the bays selected from bow for each of the ship have been compared in order to analyze the acceleration values.

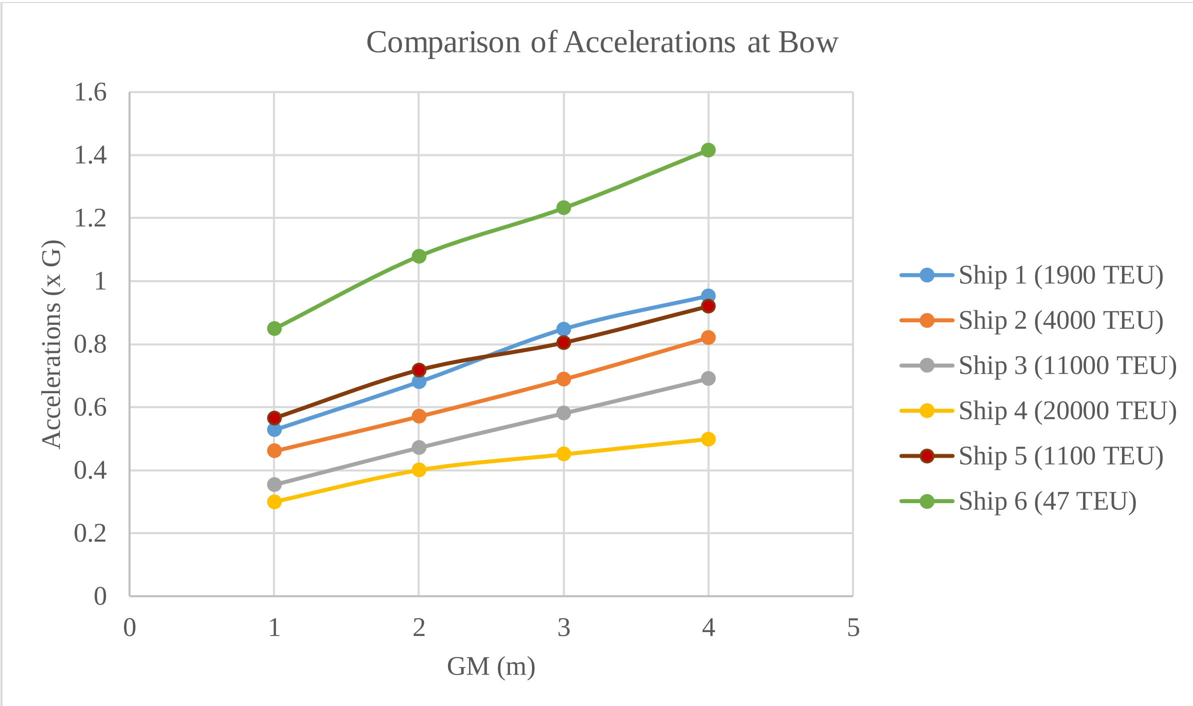



Figure 5.33. Comparison of maximum lateral accelerations at bow for all the ships over a range of GM

From Figure 5.33, it can be observed that the acceleration values tends to increase with the decrease in ship size. This means that the smallest ship (47 TEU) included in the study receives the highest amount of accelerations while the largest ship (20,000 TEU) receives the lowest amount of accelerations. This is obvious since the smallest ship with least weight will get affected the most with the encountering waves leading to high roll angles.

# 6. ANALYSIS ON STOWLASH FOR CONSTANT SPEED AS INPUT AND RESULT COMPARISON

StowLash calculates the accelerations for a particular stack of containers by defining the number of tiers, while the number of rows is always defined as 1 for a single stack. After defining the input data, the software displays the stack of the containers for which the accelerations are to be evaluated. Figure 6.1 shows an example of stack formation by StowLash containing four tiers and a single row. The 20ft container type is selected.

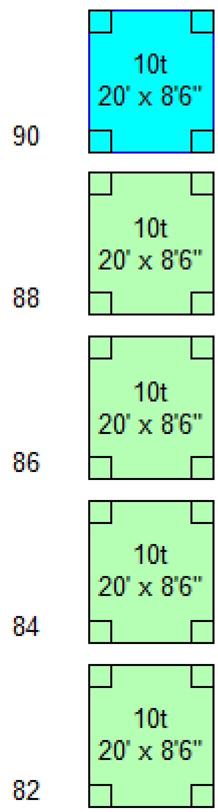



Figure 6.1. Example of container stack formation by StowLash

In order to analyze the results from StowLash and comparing them to QUERROLL, three different metacentric heights have been considered for each of the ship separately. For these three GMs, accelerations have been evaluated from StowLash and the maximum acceleration, which obviously occurs at the top most tier, is picked and compared with the value taken from QUERROLL for the same position.

To give a view of the results formulated by StowLash, a table is given for only ship 1 showing accelerations while for other ships, only the tables for comparison of maximum acceleration values are shown.

A relative error is formulated to find the difference between the two values. Positive error indicates that the acceleration value from StowLash is greater as compared to value from QUERROLL.

## 6.1. Ship 1 – 1900 TEU

For the calculation of accelerations, three different container stacks and different longitudinal positions are used as input. These stack are the same used in QUERROLL including bay number 35 from aft, bay number 21 from mid ship and bay number 1 from fore part of the ship. The calculation has been done for maximum service speed of the ship.

To have an idea, output acceleration results for the defined bays are represented in Tables 6.1, 6.2 and 6.3. Three different GM of 1 m, 3 m and 4 m have been considered. The acceleration values given by StowLash are in the opposite numbering of tiers, that is the first value belongs to the lowest tier and the last and the maximum value belongs to the top most tier.

Table 6.1. Lateral accelerations from StowLash in aft part of the ship for three different GM

| Speed (kn) | 7 Tiers | VCG (m) | LCG (m) |
|---|---|---|---|
| 18.5 | Aft Bay (35) | 17.1 | 20.4 |
| | Lateral Accelerations (x G) | | |
| GM (m) | 1 | 3 | 4 |
| | 0.490965 | 0.623555 | 0.66554 |
| | 0.500206 | 0.652115 | 0.703811 |
| | 0.509446 | 0.681087 | 0.742082 |

| | | | |
|---|---|---|---|
| | 0.518789 | 0.71006 | 0.780356 |
| | 0.528235 | 0.739032 | 0.819441 |
| | 0.537681 | 0.768004 | 0.858526 |
| | 0.547126 | 0.79746 | 0.897612 |

Table 6.2. Lateral accelerations from StowLash in mid ship for three different GM

| Speed (kn) | 6 Tiers | VCG (m) | LCG (m) |
|---|---|---|---|
| 18.5 | Mid Bay (21) | 20 | 73.3 |
| | Lateral Accelerations (x G) | | |
| GM (m) | 1 | 3 | 4 |
| | 0.480747 | 0.627464 | 0.677371 |
| | 0.490253 | 0.65705 | 0.716456 |
| | 0.499904 | 0.686639 | 0.755542 |
| | 0.509555 | 0.716227 | 0.794627 |
| | 0.519206 | 0.745816 | 0.833821 |
| | 0.528857 | 0.775404 | 0.873721 |

Table 6.3. Lateral accelerations from StowLash in fore part of the ship for three different GM

| Speed (kn) | 4 Tiers | VCG (m) | LCG (m) |
|---|---|---|---|
| 18.5 | Fore Bay (1) | 20 | 160.2 |
| | Lateral Accelerations (x G) | | |
| GM (m) | 1 | 3 | 4 |
| | 0.563068 | 0.717032 | 0.764484 |
| | 0.571898 | 0.744155 | 0.800609 |
| | 0.580728 | 0.771278 | 0.837251 |
| | 0.589557 | 0.798837 | 0.873894 |

In order to make a comparison of the results and to determine the difference, the maximum values for each bay from StowLash and QUERROLL are considered and compared for all three metacentric heights and a relative error is formulated, as represented in Table 6.4.

This comparison is performed to investigate the proximity of the results from two software for the same ships. Also the study will confirm about the status of StowLash being more conservative in the result output as compared to the QUERROLL.

Table 6.4. Maximum acceleration comparison at different longitudinal positions and GM

| **MAX LATERAL ACCELERATIONS (x G)** | | | | | | |
|---|---|---|---|---|---|---|
| | **Aft Bay** | | **Mid Bay** | | **Fore Bay** | |
| **GM (m)** | **QUERROLL** | **StowLash** | **QUERROLL** | **StowLash** | **QUERROLL** | **StowLash** |
| 1 | 0.4873 | 0.547126 | 0.4834 | 0.528857 | 0.5274 | 0.589557 |
| Relative Error (%) | 10.93 | | 8.60 | | 10.54 | |
| 3 | 0.8324 | 0.79746 | 0.8403 | 0.775404 | 0.8475 | 0.798837 |
| Relative Error (%) | -4.38 | | -8.37 | | -6.09 | |
| 4 | 0.9558 | 0.897612 | 0.9688 | 0.873721 | 0.9532 | 0.873894 |
| Relative Error (%) | -6.48 | | -10.88 | | -9.08 | |

The positive error shows that StowLash value is greater while negative error shows that QUERROLL value is greater. From Table 6.4, it is observed that only for the lowest GM of 1 m, StowLash gives considerably high design values for accelerations while for higher GM, it is no more on the conservative side. There is no fixed difference between values from both software since the errors are not fixed and fluctuate for all GM values and longitudinal positions.

The comparison interprets that for the calculation of accelerations, StowLash does not evaluate design values that can always be considered as conservative values and therefore the approximation formula used in StowLash is not much feasible to evaluate results, especially for high metacentric heights. While the large error shows that the output results from the two software carry a significant difference.

## 6.2. Ship 2 – 4000 TEU

Table 6.5. Maximum acceleration comparison at different longitudinal positions and GM

| MAX LATERAL ACCELERATIONS (x G) | | | | | | |
|---|---|---|---|---|---|---|
| | **Aft Bay** | | **Mid Bay** | | **Fore Bay** | |
| **GM (m)** | **QUERROLL** | **StowLash** | **QUERROLL** | **StowLash** | **QUERROLL** | **StowLash** |
| 1 | 0.4142 | 0.442299 | 0.405 | 0.425931 | 0.4602 | 0.478769 |
| Relative Error (%) | 6.35 | | 4.91 | | 3.88 | |
| 3 | 0.6422 | 0.631805 | 0.6524 | 0.622885 | 0.688 | 0.651864 |
| Relative Error (%) | -1.65 | | -4.74 | | -5.54 | |
| 4.5 | 0.7825 | 0.730027 | 0.8073 | 0.726846 | 0.8219 | 0.731375 |
| Relative Error (%) | -7.19 | | -11.07 | | -12.38 | |

## 6.3. Ship 3 – 11,000 TEU

Table 6.6. Maximum acceleration comparison at different longitudinal positions and GM

| MAX LATERAL ACCELERATIONS (x G) | | | | | | |
|---|---|---|---|---|---|---|
| | **Aft Bay** | | **Mid Bay** | | **Fore Bay** | |
| **GM (m)** | **QUERROLL** | **StowLash** | **QUERROLL** | **StowLash** | **QUERROLL** | **StowLash** |
| 1 | 0.3435 | 0.356052 | 0.3314 | 0.342192 | 0.3535 | 0.367366 |
| Relative Error (%) | 3.53 | | 3.15 | | 3.77 | |
| 3.16 | 0.5811 | 0.519893 | 0.5713 | 0.507527 | 0.5805 | 0.521695 |
| Relative Error (%) | -11.77 | | -12.57 | | -11.27 | |
| 7 | 0.976 | 0.706735 | 0.9684 | 0.697126 | 0.945 | 0.684206 |
| Relative Error (%) | -38.10 | | -38.91 | | -38.12 | |

## 6.4. Ship 4 – 20,000 TEU

Table 6.7. Maximum acceleration comparison at different longitudinal positions and GM

| MAX LATERAL ACCELERATIONS (x G) | | | | | | |
|---|---|---|---|---|---|---|
| | Aft Bay | | Mid Bay | | Fore Bay | |
| GM (m) | QUERROLL | StowLash | QUERROLL | StowLash | QUERROLL | StowLash |
| 1 | 0.2938 | 0.334781 | 0.2836 | 0.322183 | 0.2997 | 0.333585 |
| Relative Error (%) | 12.24 | | 11.98 | | 10.16 | |
| 4 | 0.5081 | 0.452286 | 0.5 | 0.441217 | 0.4986 | 0.436881 |
| Relative Error (%) | -12.34 | | -13.32 | | -14.13 | |
| 7 | 0.6673 | 0.547477 | 0.6605 | 0.537951 | 0.6392 | 0.515501 |
| Relative Error (%) | -21.89 | | -22.78 | | -24.00 | |

## 6.5. Ship 5 – 1100 TEU

Table 6.8. Maximum acceleration comparison at different longitudinal positions and GM

| MAX LATERAL ACCELERATIONS (x G) | | | | | | |
|---|---|---|---|---|---|---|
| | Aft Bay | | Mid Bay | | Fore Bay | |
| GM (m) | QUERROLL | StowLash | QUERROLL | StowLash | QUERROLL | StowLash |
| 1 | 0.531 | 0.654597 | 0.513 | 0.63145 | 0.5652 | 0.6862 |
| Relative Error (%) | 18.88 | | 18.76 | | 17.64 | |
| 3 | 0.8215 | 0.91654 | 0.7827 | 0.887847 | 0.8046 | 0.873499 |
| Relative Error (%) | 10.37 | | 11.84 | | 7.89 | |
| 4.5 | 0.9982 | 1.096653 | 0.9439 | 1.063209 | 0.9389 | 0.992639 |
| Relative Error (%) | 8.98 | | 11.22 | | 5.41 | |

## 6.6. Ship 6 – 47 TEU

Table 6.9. Maximum acceleration comparison at different longitudinal positions and GM

| MAX LATERAL ACCELERATIONS (x G) | | | | | | |
|---|---|---|---|---|---|---|
| | Aft Bay | | Mid Bay | | Fore Bay | |
| GM (m) | QUERROLL | StowLash | QUERROLL | StowLash | QUERROLL | StowLash |
| 1 | 0.784 | 0.770581 | 0.768 | 0.722777 | 0.8484 | 0.813674 |
| Relative Error (%) | -1.74 | | -6.26 | | -4.27 | |
| 3 | 1.0745 | 1.068969 | 1.07 | 0.979713 | 1.2317 | 1.155265 |
| Relative Error (%) | -0.52 | | -9.22 | | -6.62 | |
| 4 | 1.2097 | 1.227748 | 1.2112 | 1.11682 | 1.4156 | 1.33398 |
| Relative Error (%) | 1.47 | | -8.45 | | -6.12 | |

## 6.7. Discussion

After performing the analysis for ship 1, the similar trend of errors were found for all the ships as discussed for ship 1. From Table 6.4 to 6.9, the calculated relative error illustrates the adaptability of the software code used. The major task behind the comparison of accelerations was to determine that if the approximation formula is effective enough to cater the calculations for different sized vessels and to check whether the results from StowLash are always on the conservative side.

Only for ship 5 (Table 6.8), the positive errors are displayed, indicating that StowLash results for design values of accelerations are higher than QUERROLL. The large values of relative error for all the ships and for almost all metacentric heights and longitudinal positions illustrates that the approximation formula used is not reliably efficient and does not evaluate the accelerations under defined values.

# 7. IMPACT OF REDUCING SPEED AS INPUT PARAMETER

The second task of this study is to determine the impact created on accelerations by reducing speed of the ship as input parameter for QUERROLL and StowLash. The accelerations are calculated at different speeds lower than the maximum service speed of the ship and a comparison is made for the results.

StowLash has a lower speed limit of 8 knots as input and does not evaluate any results if the the speed is entered below this value. Therefore the lowest vessel speed considered for this study has been selected as 8 knots for all the ships. The calculations are made for speed inputs starting from 8 knots and increasing with an interval of 2 knots up to the maximum service speed of the given ship.

Other parameters including longitudinal positions of the selected stacks (bay numbers) and the metacentric heights are considered the same as in the previous analysis.

Accelerations are evaluated for different speeds from the two software and the maximum acceleration is selected for each position and metacentric height to perform the comparison, similar to the analysis done in the previous task.

For each ship, three different graphs are generated, one for each metacentric height to display the behavior of the accelerations for different reduced speed values.

- **Ship 1 – 1900 TEU**

The graph displayed in the figures from Figure 7.1 to 7.3, illustrates the behavior of accelerations with the reducing speed of the ship at different metacentric heights.

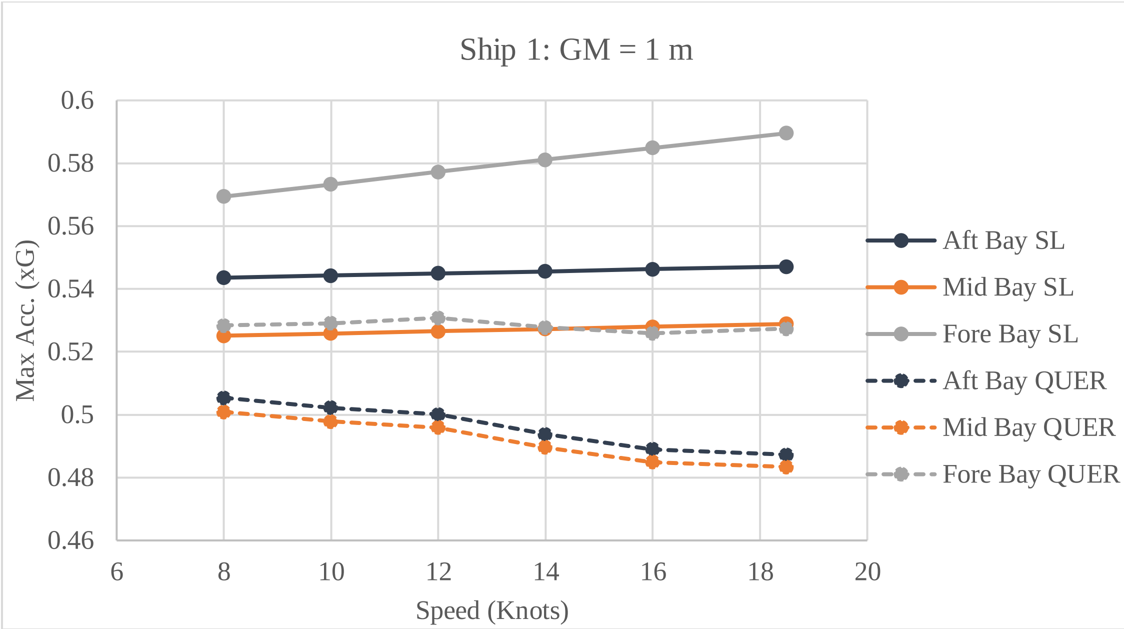



Figure 7.1. Ship 1 - Comparison of max accelerations for reduced speeds with 1 m GM

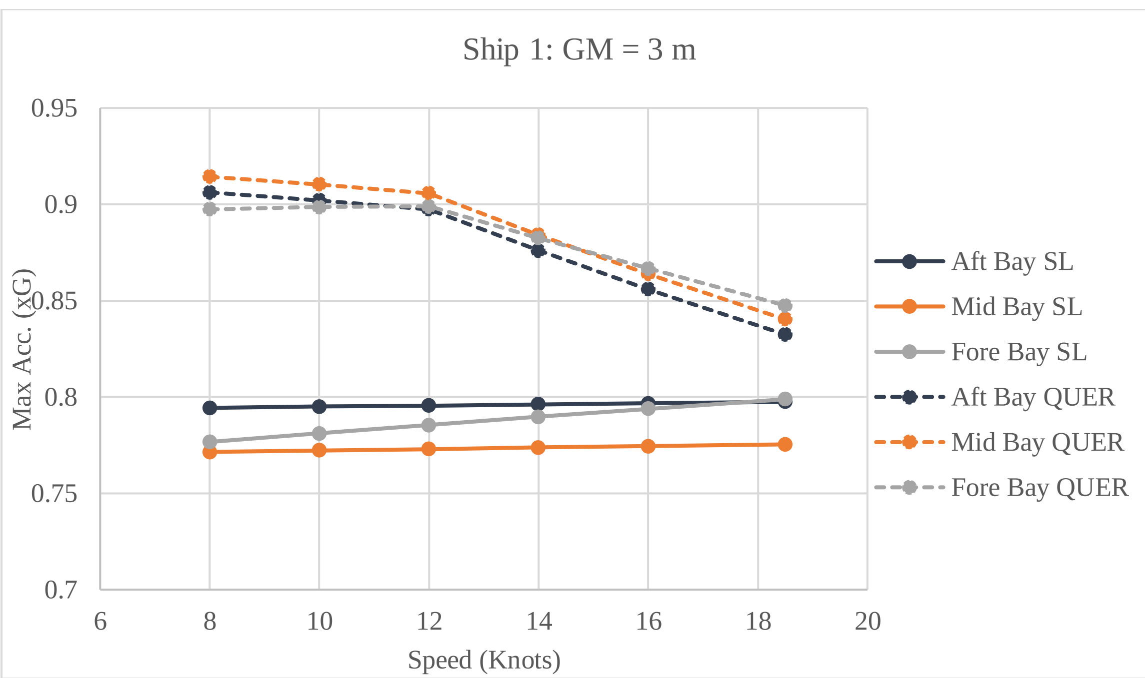



Figure 7.2. Ship 1 - Comparison of max accelerations for reduced speeds with 3 m GM

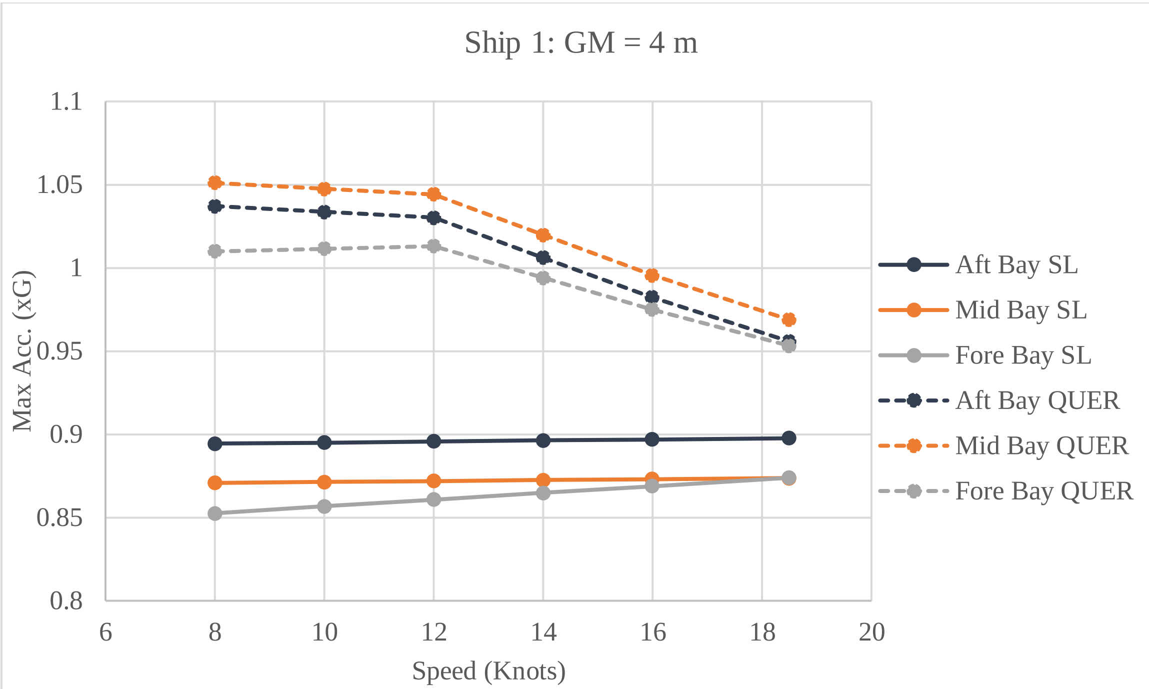



Figure 7.3. Ship 1 - Comparison of max accelerations for reduced speeds with 4 m GM

From the figures, it can be observed that the calculated accelerations from StowLash are much lower as compared to the results from QUERROLL. StowLash results show a linear or constant trend in the acceleration values with the reducing speed. It is observed that the accelerations for the aft part and mid ship remains almost constant throughout lower speeds while the accelerations at bow significantly decreases with the reduction in speed. The reason behind is that the vertical acceleration contributes indirectly via the roll inclination, resulting in large lateral accelerations in the fore part. Also the bow gets subjected to most of the waves when a ship navigates in a seaway, therefore it receives more forces as compared to aft and mid ship. Hence the accelerations in bow becomes lower as the ship navigates and strike the waves with reduced speeds.

By witnessing the QUERROLL results in the graphs, it is observed that the accelerations show a subtle drop near speed of 12 knots and then further decreases up to the maximum service speed. This is due to the fact that QUERROLL performs the acceleration evaluation at 2/3$^{rd}$ of the maximum service speed. It is assumed that a ship does not navigate at its maximum service speed because of the resistance by waves and wind that limits the ship's speed. Therefore, an average ship's cruising speed is the 2/3rd of its service speed, as consider by the program code. For the same reason, the speed used in the calculation by QUERROLL is actually the 2/3rd of the speed that has been used as input.

Ship 1 has a maximum speed of 18.5 knots and 2/3rd of which makes 12.3 knots. From graphs, the acceleration shows a drop near 12 knots, therefore it is perceived that QUERROLL gives no reliable results for higher speeds, which are actually greater than the input speed used.

Considering the 2/3rd speed criteria of QUERROLL, taking the example for 4 m GM results for the fore bay (Figure 7.3), acceleration calculated by QUERROLL at maximum speed of 18.5 knots gives a value of 0.9532. According to the criteria, this speed should be close to the acceleration calculated by StowLash at 12.3 knots, but it is actually around 0.8607. Therefore the results from the two software display a significant difference at various speeds.

- **Ship 2 – 4000 TEU**

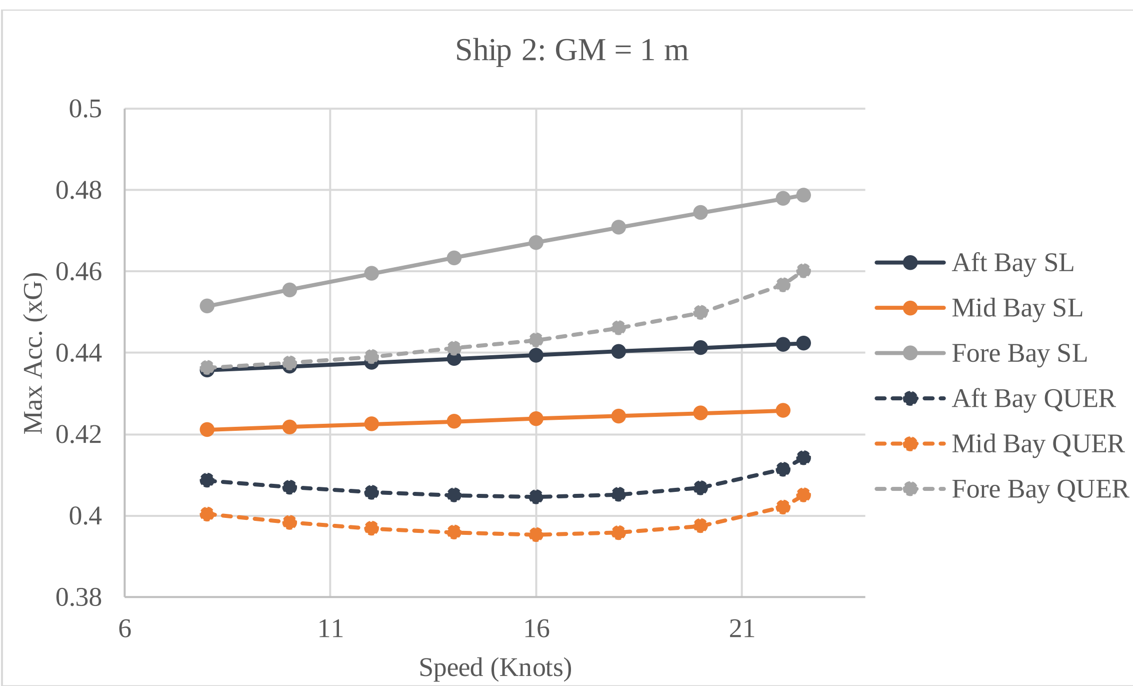



Figure 7.4. Ship 2 - Comparison of max accelerations for reduced speeds with 1 m GM

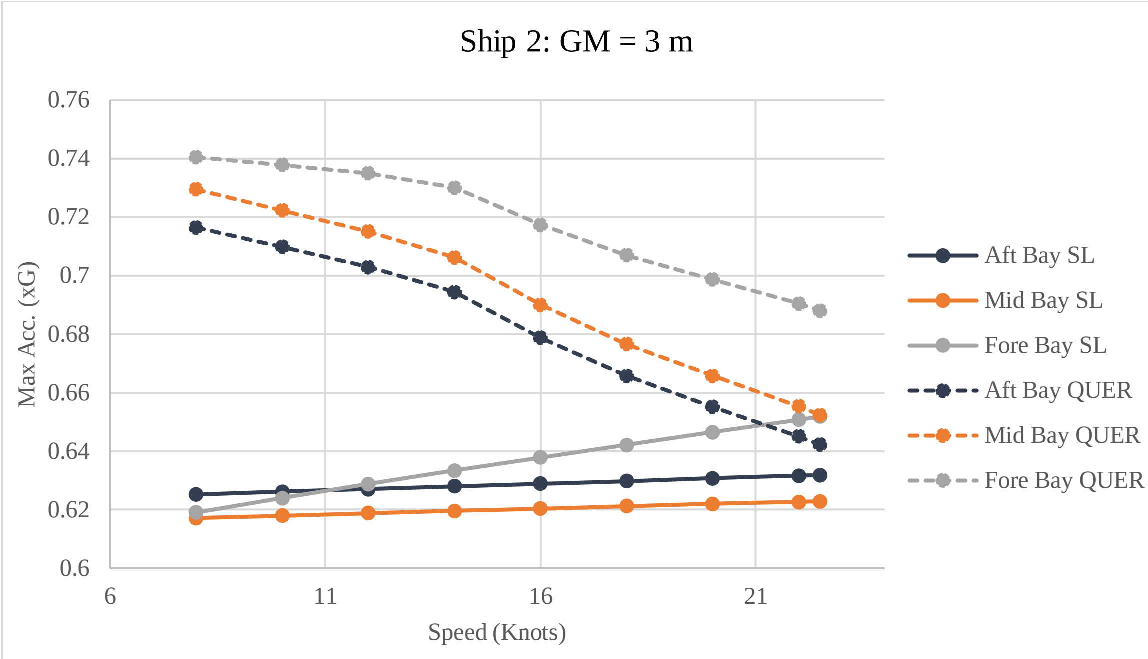



Figure 7.5. Ship 2 - Comparison of max accelerations for reduced speeds with 3 m GM

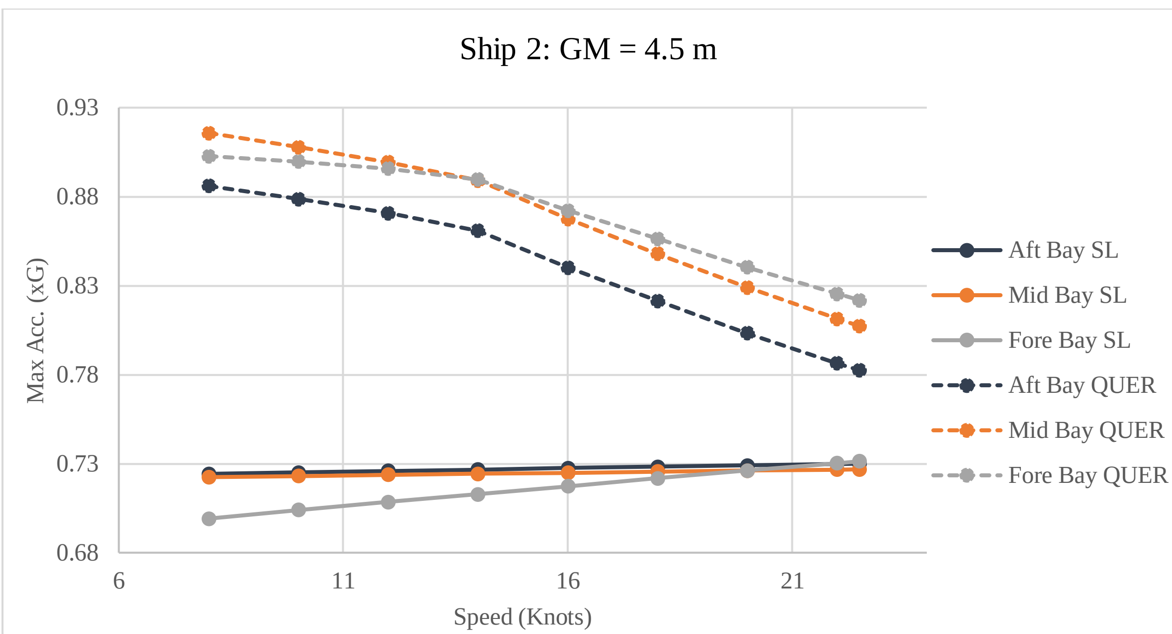



Figure 7.6. Ship 2 - Comparison of max accelerations for reduced speeds with 4.5 m GM

Ship 2 has a maximum service speed of 22.5 knots. In the Figure 7.4 to 7.6, StowLash results display a stable trend of acceleration decrement with ship's bow showing a significant drop of accelerations at lower speeds.

For QUERROLL results at the lowest GM of 1 m (Figure 7.4), the accelerations for aft and mid ship display an irregular trend with reduction and increment across the range of speeds while bow shows a regular decrement with the reduction in speed.

For higher GM (Figure 7.5 and 7.6), the decreasing trend of acceleration for higher speeds is similar to ship 1 where a drop is observed at around 2/3rd of the ship's maximum speed.

- **Ship 3 – 11,000 TEU**

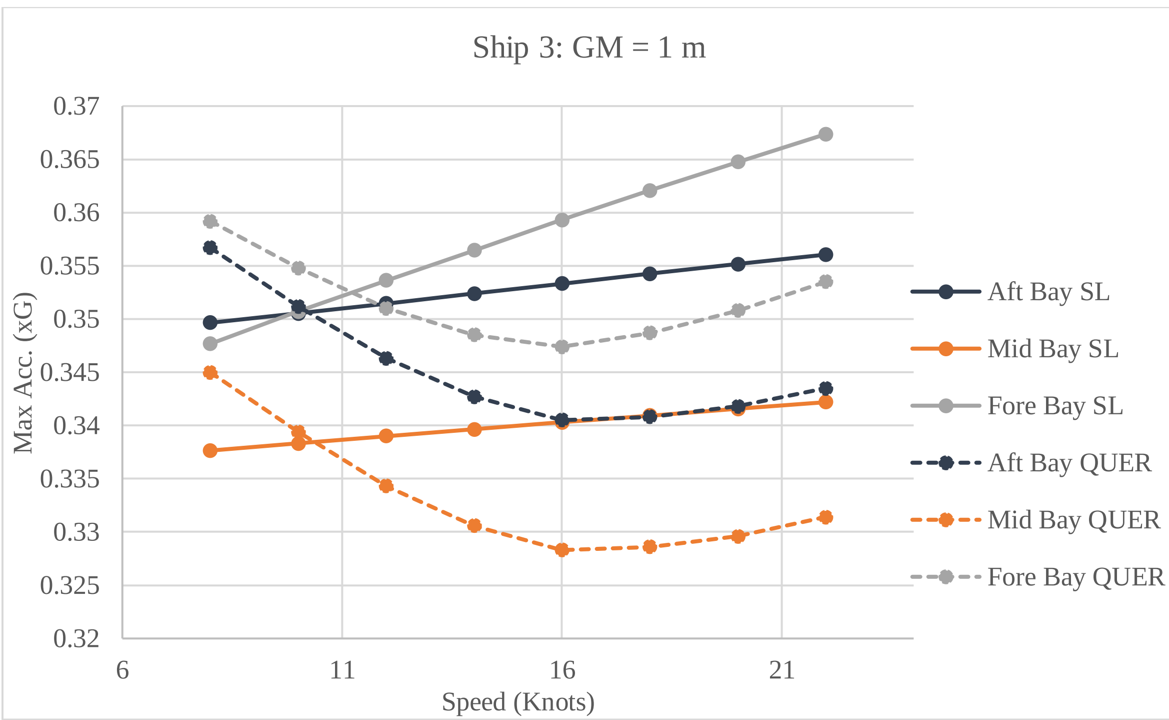



Figure 7.7. Ship 3 - Comparison of max accelerations for reduced speeds with 1 m GM

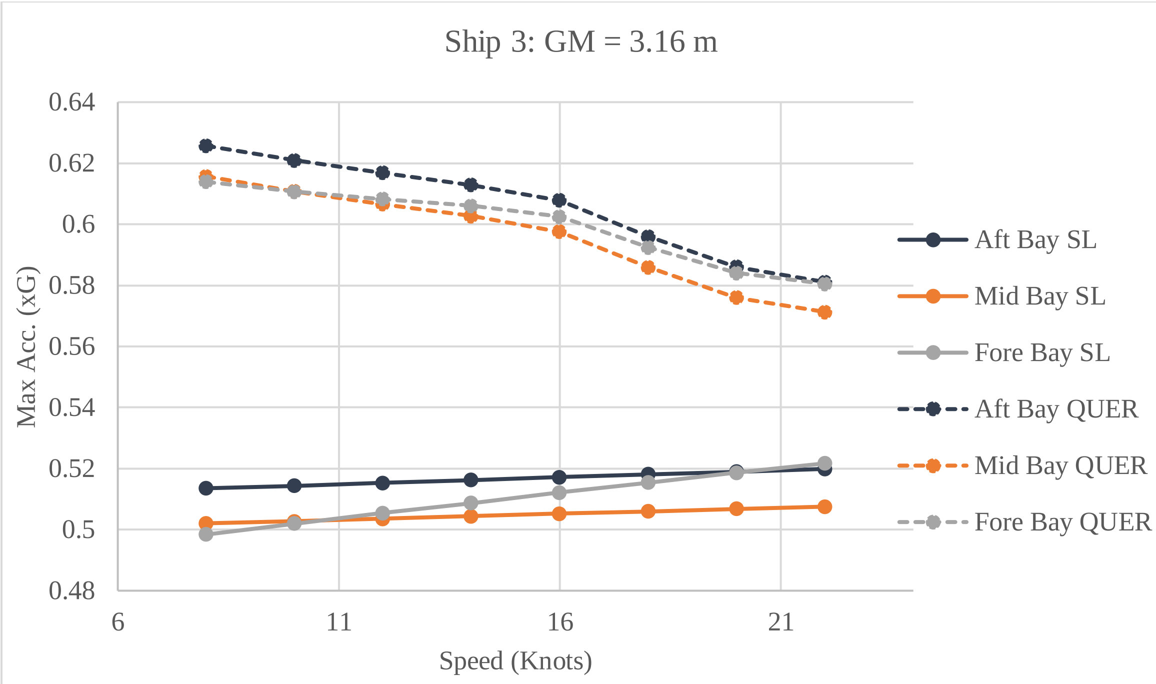



Figure 7.8. Ship 3 - Comparison of max accelerations for reduced speeds with 3.16 m GM

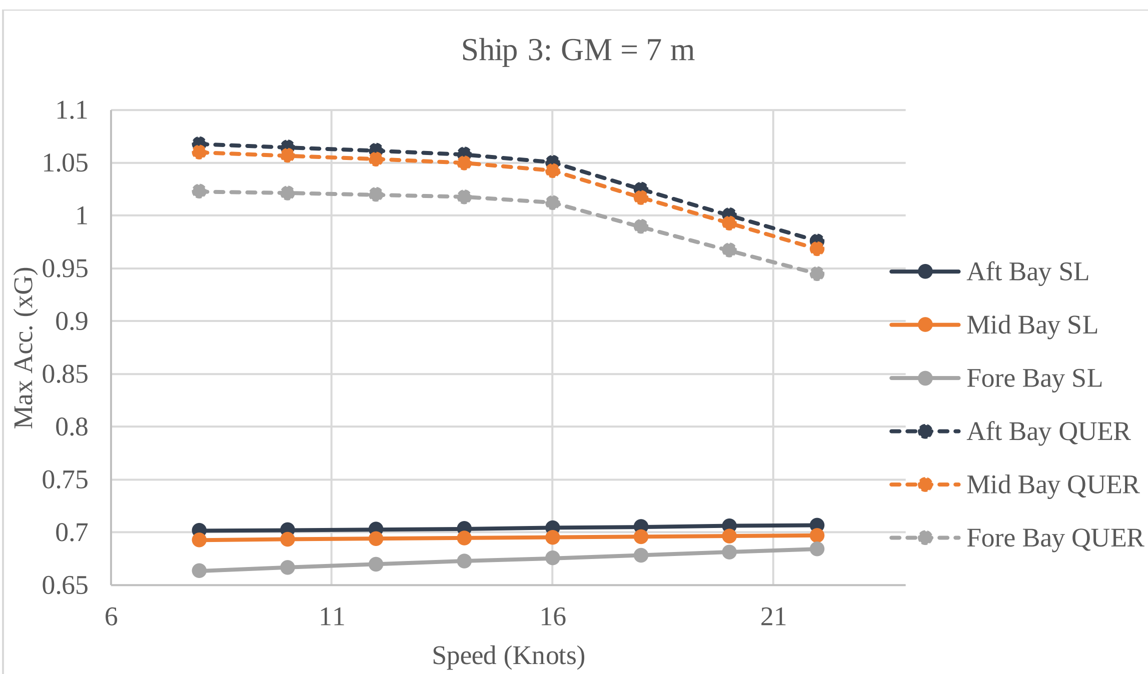



Figure 7.9. Ship 3 - Comparison of max accelerations for reduced speeds with 7 m GM

The maximum service speed of ship 3 is 22 knots. Figure 7.7 to 7.9 shows almost the similar trends of acceleration changes as displayed for ship 2. The StowLash illustrates steady results for higher GM while for lower GM of 1 m, the accelerations at all parts of the ship decrease with a significant amount with the decreasing speed.

QUERROLL results show similar irregular trend as ship 2 for lower GM while for higher GM, a drop in acceleration values at around 2/3rd of the maximum speed is observed.

- **Ship 4 – 20,000 TEU**

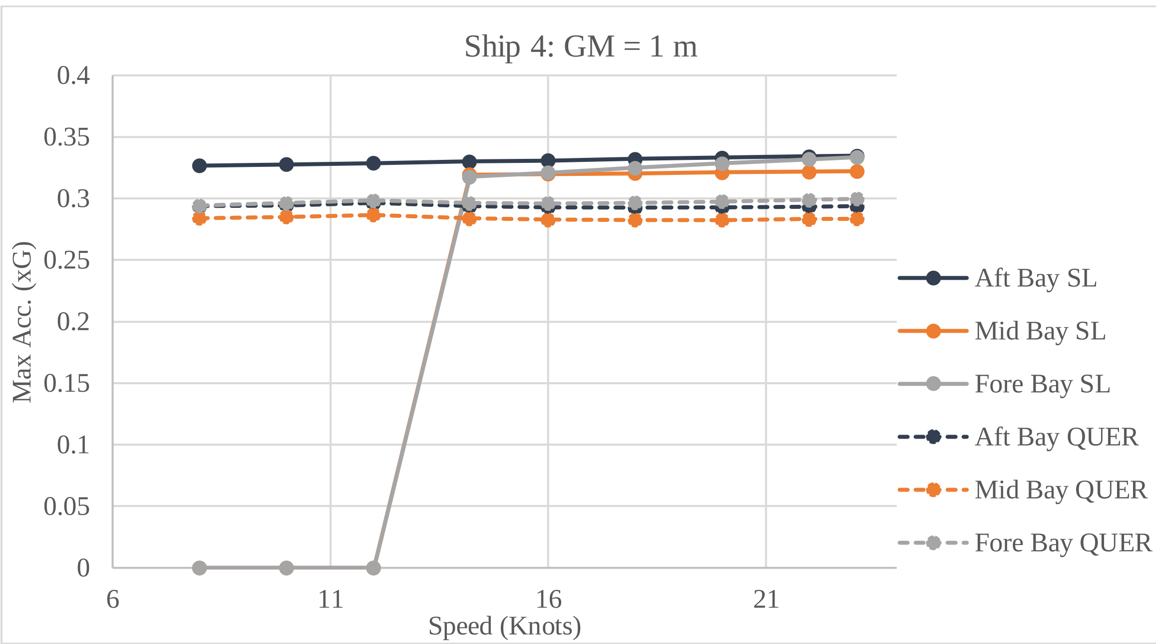



Figure 7.10. Ship 4 - Comparison of max accelerations for reduced speeds with 1 m GM

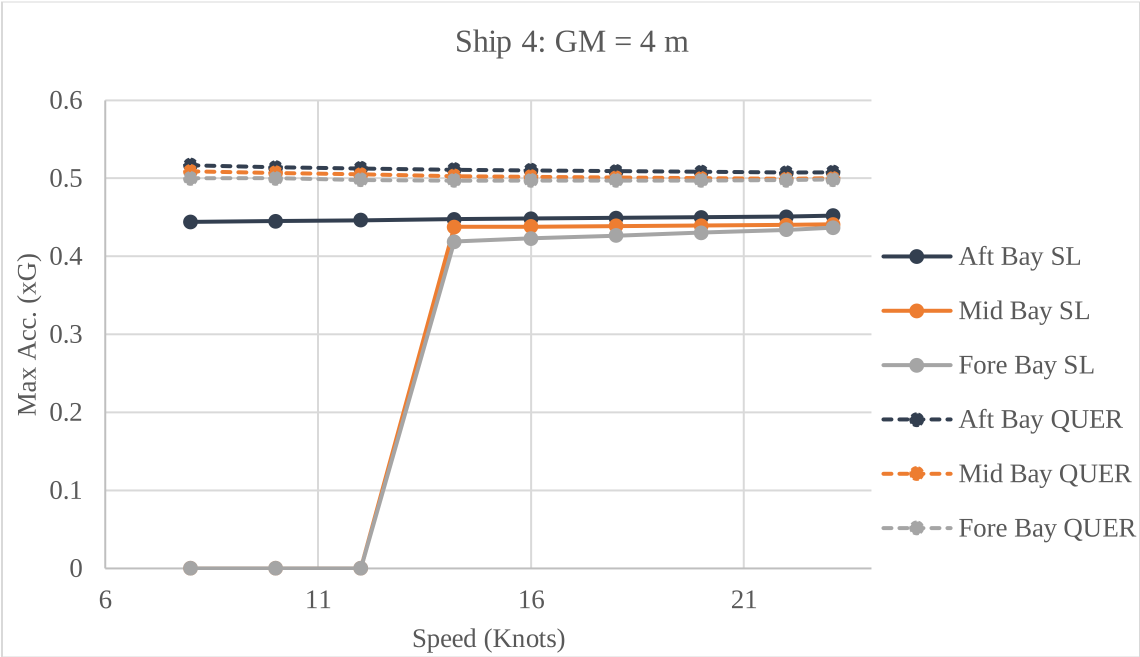



Figure 7.11. Ship 4 - Comparison of max accelerations for reduced speeds with 4 m GM

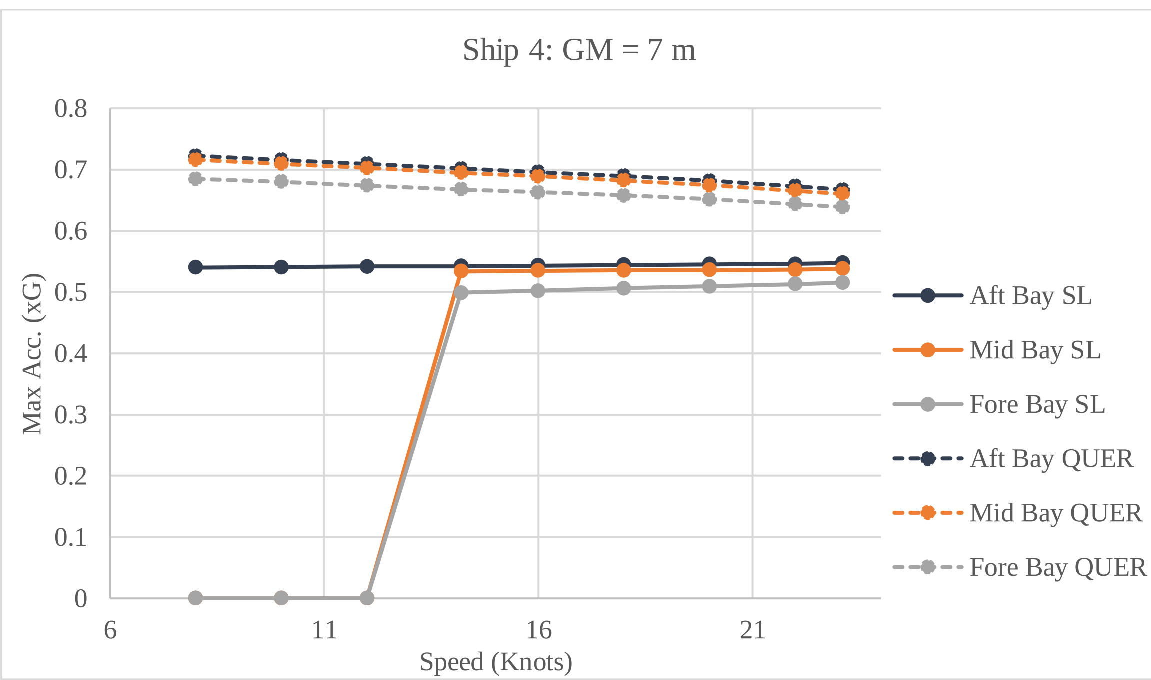



Figure 7.12. Ship 4 - Comparison of max accelerations for reduced speeds with 7 m GM

Ship 4 is the biggest ship included in the analysis with a maximum service speed of 23.1 knots. Figure 7.10 to 7.12 shows the acceleration changes from StowLash with a normal graph line and it is observed that for mid and fore part of the ship, the accelerations are zero at speed of 8 knots and they achieve some value at 14.2 knots. The reason behind is StowLash was unable to perform calculations for such lower speed for ultra large ship with maximum service speed of 23.1 knots. While for aft part of ship, the acceleration values are formulated perfectly.

For such large sized container ships, the lower speed input limit of StowLash of 8 knots is invalid, though StowLash accepts the input but performs no evaluation and the results are always null.

For the QUERROLL results, it is witnessed that the acceleration changing trend with the reducing speed is almost linear and constant for lower GM while for higher GM, it tends to increase with the decreasing speed. The values are close to the output values of StowLash and no such subtle drop or change in accelerations is observed which indicates that for such large sized vessels, QUERROLL is efficient to perform evaluation from high to low speeds with decisive results.

- **Ship 5 – 1100 TEU**

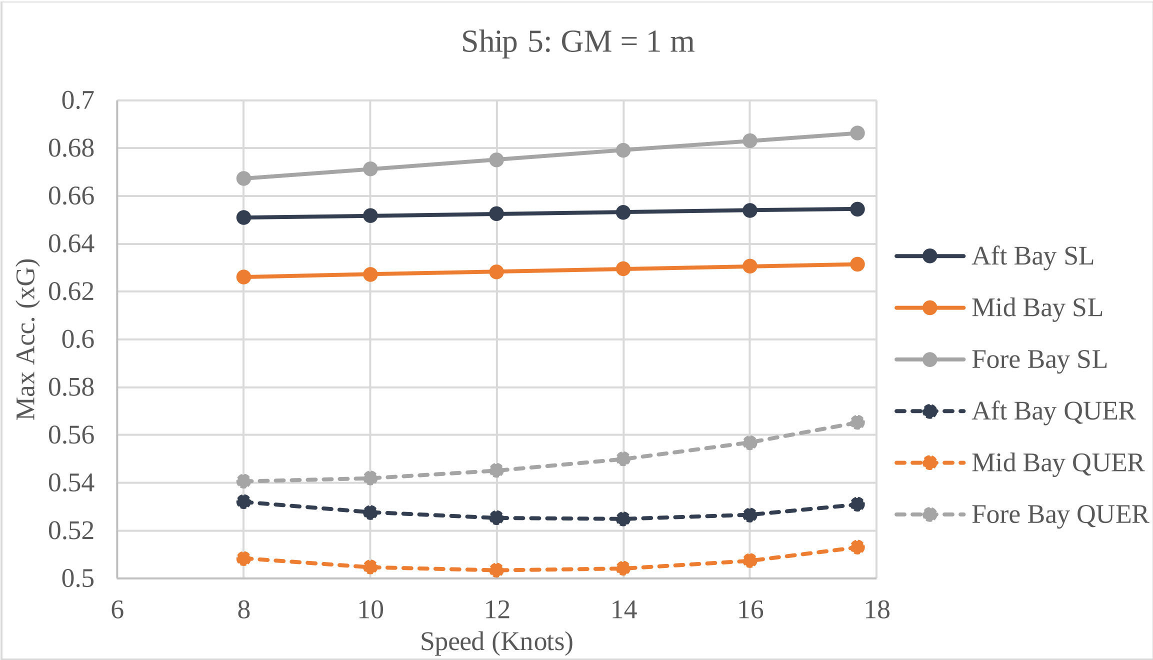



Figure 7.13. Ship 5 - Comparison of max accelerations for reduced speeds with 1 m GM

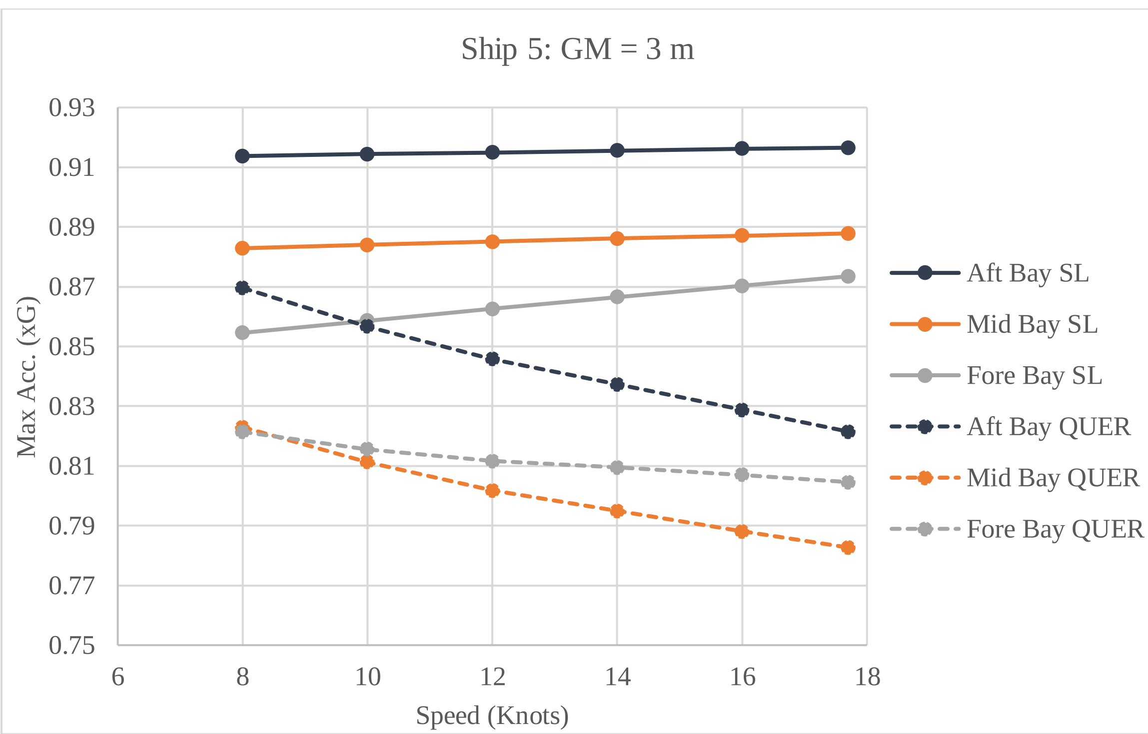



Figure 7.14. Ship 5 - Comparison of max accelerations for reduced speeds with 3 m GM

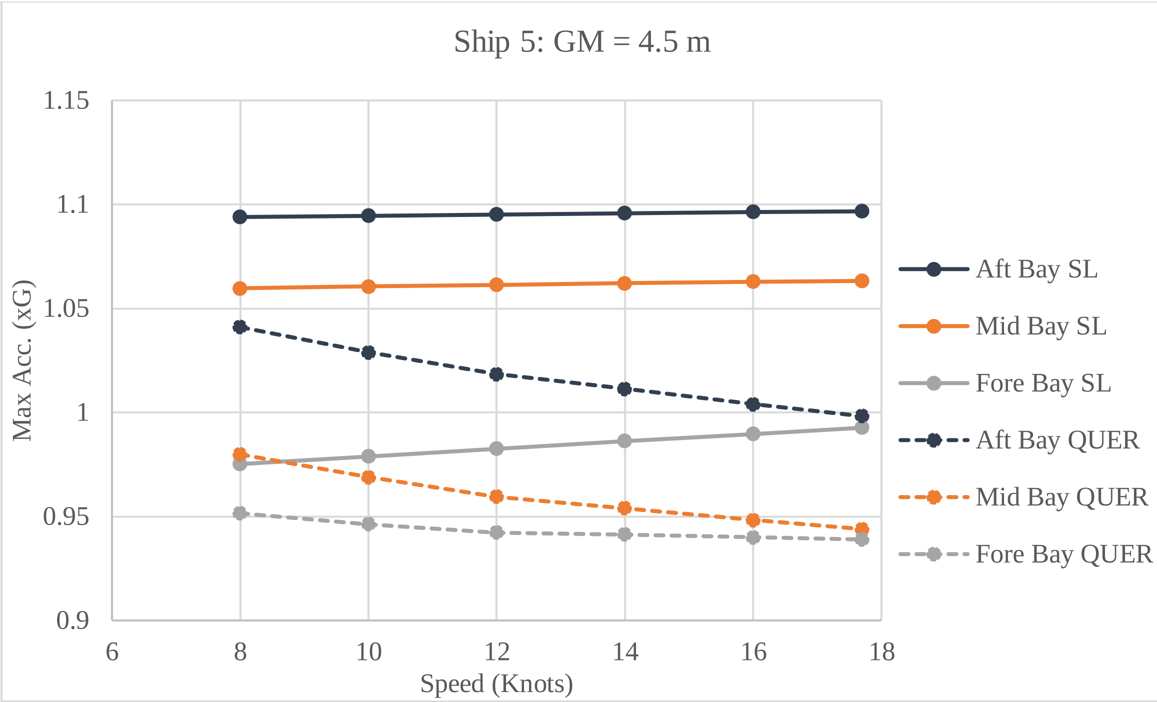



Figure 7.15. Ship 5 - Comparison of max accelerations for reduced speeds with 4.5 m GM

Ship 5 with maximum service speed of 17.7 knots is the only ship in this study for which the StowLash delivered conservative results and the accelerations for all metacentric heights and speeds were higher as compared to the results from QUERROLL.

Figure 7.13 to 7.15 shows that StowLash displayed a linear trend of acceleration changes with the change in bow being the most significant.

The results from QUERROLL shows the similar trend as for previous ships, except the evaluated accelerations are lower than StowLash in all cases.

- **Ship 6 – 47 TEU**

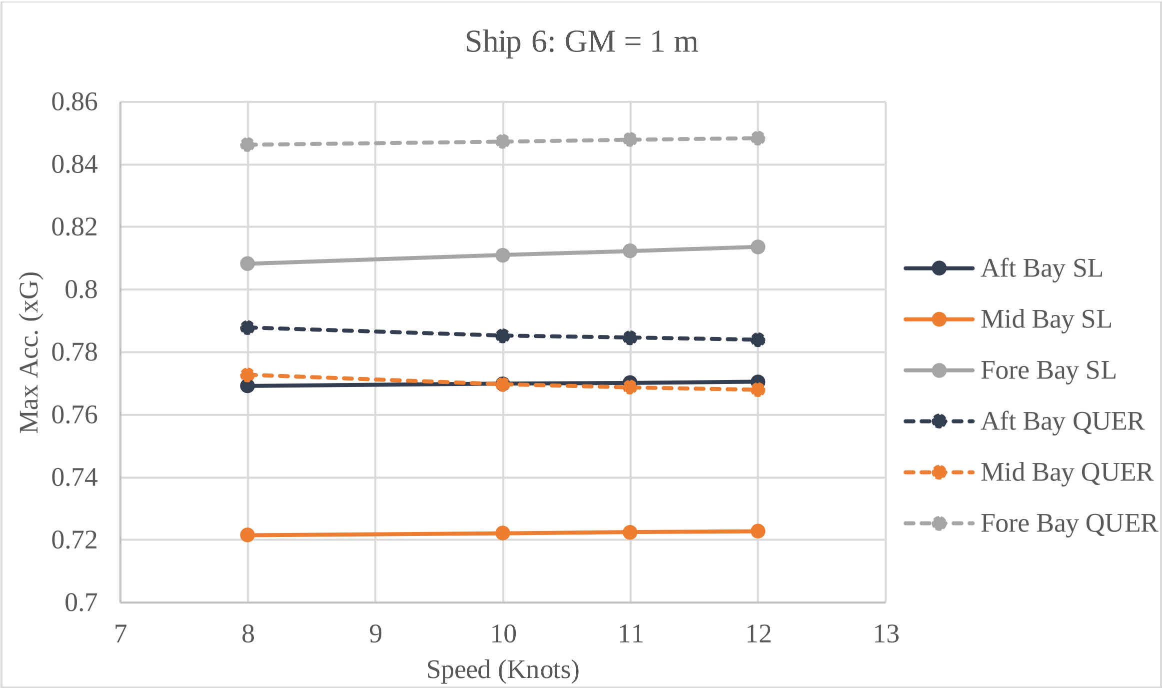



Figure 7.16. Ship 6 - Comparison of max accelerations for reduced speeds with 1 m GM

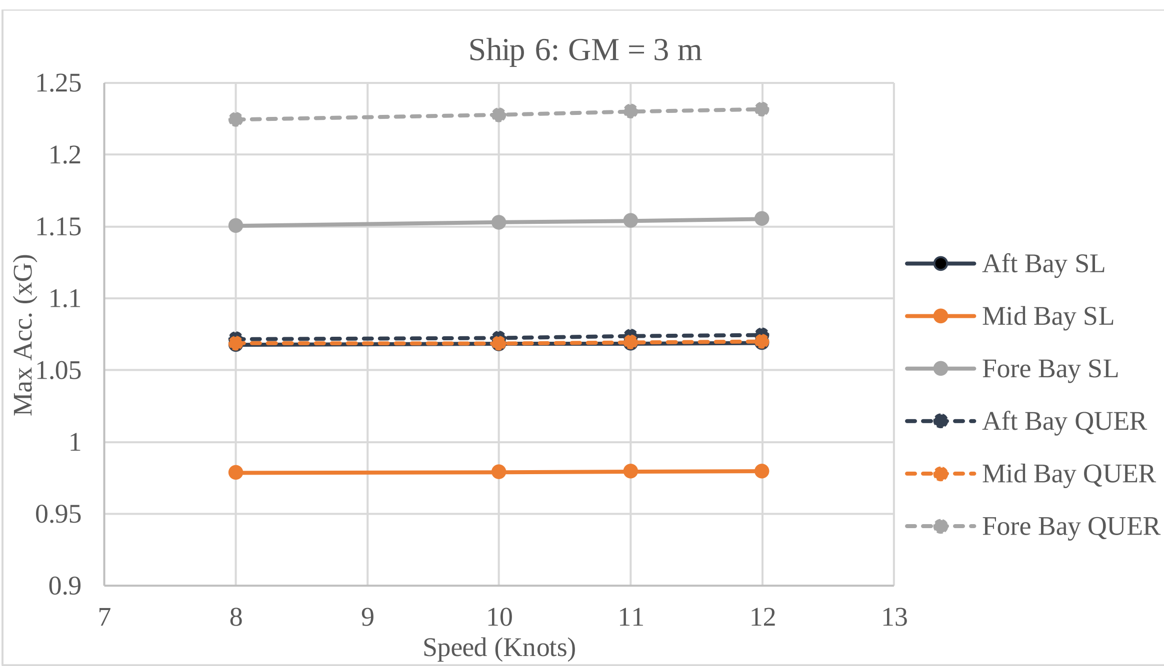



Figure 7.17. Ship 6 - Comparison of max accelerations for reduced speeds with 3 m GM

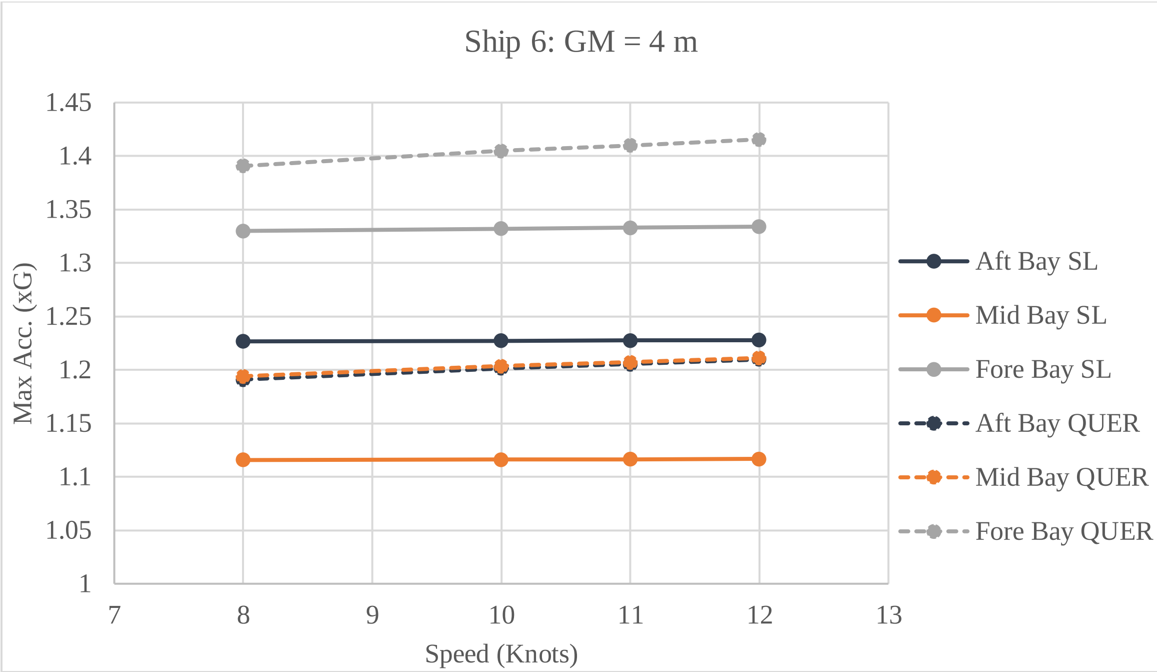



Figure 7.18. Ship 6 - Comparison of max accelerations for reduced speeds with 4 m GM

Ship 6 is the smallest ship included in the study with a maximum service speed of only 12 knots. From Figure 7.16 to 7.18, it is observed that the results from both software programs display a linear and constant trend of acceleration change for all metacentric heights.

The results delivered by QUERROLL depicts a decrease in accelerations with the reducing speed for higher GM, while for lower GM, the change is almost constant without a significant increment or decrement.

The acceleration changes from StowLash output results are similar to all the previous analyzed ships, indicating that the software code is efficient and feasible for different sized vessels ranging from very short to ultra large ships.

## 7.1. Discussion

After analyzing the results and the graphs, it is evident that for different types and sizes of ships, StowLash code displayed feasible results in terms of acceleration changes since the output graph displayed a constant trend and the changes of acceleration by varying the speed are linear and similar for all six ships included in the study. However, the design values are lower as compared to the values evaluated by QUERROLL except for the ship 5.

On the other hand, QUERROLL laid out irregular result patterns for different sized ships and the acceleration values determined were always higher than the values from StowLash. The code also did not show any stable evaluation regarding the 2/3$^{rd}$ speed convention and for ship 4, 5 and 6 there was no such exquisite drop of accelerations observed above 2/3$^{rd}$ value of the maximum service speed.

# 8. PROPOSAL

After analyzing the results under different conditions and for a variety of ships from very short to ultra large container ships, it is observed that the large differences in the results from two software demands modification in either the software code or approximation method. It might be the inaccuracy of the approximation formula generated by ACC program system of QUERROLL that exhibits imprecise accelerations, especially for lower metacentric heights.

After performing the first task of the objective in which the calculations were made at constant maximum service speed of each ship, it became evident that QUERROLL lacks the consistency regarding ship sizes and cargo capacity since it produced relatively lower acceleration values only for ship 5 (1100 TEU). Also the negative errors in comparison for all the ships (except ship 5) interprets that StowLash cannot be considered to formulate conservative design acceleration values when compared to QUERROLL.

From the analysis in the second task for reduced speeds, QUERROLL displayed an increasing trend of accelerations for almost all cases of different metacentric heights with the reduction in speed. It is impractical to accept the fact that the ship experience greater forces while navigating at slower speeds amidst keeping the draught, sea state and other parameters constant. Therefore at reduced speed as input, QUERROLL formulation is inadmissible, except for the largest ship 4 and the smallest ship 6 where it displayed quite constant results at reduced speeds. Still it is not possible to propose a justification for a particular range of lengths of ships for which approximation formula is perfectly valid and practical.

Observing all the errors and inaccuracies, it is proposed that either of the two software require amendments and improvements. It must be investigated first that which code has bugs and is not accurate for certain conditions. It should be checked for QUERROLL if the code delivers correct and practical values of accelerations for certain conditions and input parameters. On the other hand for StowLash, it must be examined whether the approximation in StowLash is reliable and feasible for the actual ship design or if there is a need to revise and modify the approximation method. The rules of DNV GL require the application of the approximation that has been implemented in StowLash. Consequently, there is a need to verify that it is still evaluating realistic conservative acceleration values, and if not then it needs to be revised to cover actual ship designs.

In StowLash, the factor that displayed inoperative results is the limit for lower speed, which is 8 knots defined in the code. This lower limit worked fine for all ships except for the largest ship 4 with maximum service speed of 23.1 knots for which the software developed null results at 8 knots. The lowest speed it took into account to perform the evaluation was 14.2 knots. Therefore for ultra large container ships with modern hull shapes and larger beams, probably above a cargo capacity of 20,000 TEU, StowLash lower speed limit has to be modified in order to develop calculations at speed up to at least 8 knots.

# 9. CONCLUSION

The major objectives of the study established in section 1.4 were achieved during this study. The importance of perfectly defining the hull lines into the software program and the influence of the parameters included as input was discussed in section 5.1 during the study of ship 1. A method for improving hull line interpolating curves and avoiding the irregular extension of curves was proposed. Other than this, an idea with the motivation to improve the maximum roll angles was proposed by introducing rudder as part of the frame and including in the development of ship's hull lines.

Moreover, the lateral accelerations from QUERROLL in three different parts of ship and for a range of metacentric heights starting from low to high were determined and studied through the graphs for each ship in section 5. Later, the lateral accelerations for the same conditions were determined from StowLash and a comparison was performed in section 6 to analyze the result difference and to make a study whether StowLash is capable of evaluating design values that are on the conservative side.

The second task of the objective was achieved in section 7 where a study was made on the acceleration values from the two software at lower speeds and for different metacentric heights. The inaccuracy of approximation formula was exemplified by the comparison graphs where the acceleration changes with the reduction in speed depicted irrational trend. The imprecision of lower defined limit of speed as input in StowLash for ultra large container ship is also raised while doing the comparison of ship 4, where the program started to exhibit the results at much higher speed input.

Finally, the proposals were made in section 8 declaring the need to investigate the software codes and to carry out modification and revision of the approximation method where required.

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