



**CHALMERS**  
UNIVERSITY OF TECHNOLOGY



# Operability of the Visby class corvette with regards to sea conditions

MASTER'S THESIS (MMSX30)

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Operability of the Visby class corvette with regards to sea conditions

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Cover: The Visby class corvette HSwMS Karlstad in waves.

Photo: Jimmie Adamsson/the Swedish Armed Forces (Adopted from Swedish Armed Forces, 2021)

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The master thesis (MMSX30) is a 30 HEC (Higher Education Credits) thesis, finalizing the master's program for a degree in naval architecture and ocean engineering at Chalmers University of Technology. The thesis is written for the department of Mechanics and Maritime sciences.

## Abstract

The project *Operability of the Visby class corvette with regards to sea conditions* is meant to accomplish two main tasks. First it is to investigate what a reasonable limit on ship motions on the Visby class corvettes should be to make sure that the crew remains able to perform their duties and that all systems are working as required. The second task is to investigate the operability at each main mission with regard to these limits, as well as the circumstances of the occasions where the ship fails with any of the criteria.

The selected criteria focus on human performance. They include Motion Sickness Incidence (MSI) index to relate motion to cognitive performance in places such as the bridge, and Motion Induced Interruption (MII) index to quantify the effect on the ability to perform manual work. A slamming criterion is also used because of the negative effects on crew health and comfort. Criteria that focus on ship and system performance include roll and pitch limits to ensure the capability to launch missiles and torpedoes, and a submergence criterion for an exhaust pipe opening.

Several relevant mission sets are considered, and one scenario of an escorting mission to Gotland is presented in a bit more detail, where the statistical distribution of wave directions for each sea state is taken into account. It is concluded that the operability, depending on mission and season, is around 90 %, higher for some missions, particularly when course deviations are allowed. Most of the criteria are limiting in some situation with none being obviously over represented.

Keywords: Operability, Seakeeping, Seakeeping criteria, Strip theory, Naval architecture, Ship motions, Motion induced interruptions.

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## Nomenclature

### Latin symbols

$C_f$	Frictional coefficient
$D$	Wave spreading function
$D_{\text{MII}}$	Duration of MII event
$E_{\text{task}}$	Task effectiveness
$Fn$	Froude number
$Fn_{\nabla}$	Froude number based on displaced volume
$g$	Gravitational acceleration [ $\text{m/s}^2$ ]
$h$	Height of persons center of gravity [m]
$H_s$	Significant wave height [m]
$l$	Half stance width [m]
$L_{WL}$	Water line length [m]
$\dot{N}$	Rate of events [ $\text{events/h}$ ]
$\ddot{s}_i$	Local acceleration in degree of freedom $i$ [ $\text{m/s}^2$ ]
$S^\zeta$	Wave spectrum [ $\text{m}^2\text{s}$ ]
$S_e^\zeta$	Encounter wave spectrum [ $\text{m}^2\text{s}$ ]
$S^\eta$	Response spectrum [ $\text{m}^2\text{s}$ ]
$T$	Draft of the ship [m]
$T_e$	Mean zero crossing period of motions [s]
$T_p$	Mean wave peak period [s]
$T_{ref}$	Reference time period [h]
$T_z$	Mean wave zero crossing period [s]
$v$	Speed of the ship [ $\text{m/s}$ ]

### Greek symbols

$\gamma$	Peak enhancement factor
$\zeta$	Wave elevation [m]
$\eta_i$	Ship motion in degree of freedom $i$ [m]

$\ddot{\eta}_i$	Ship acceleration in degree of freedom $i$ [ $\text{m/s}^2$ ]
$\theta$	Spreading angle of wave component
$\mu$	Course relative to waves main direction
$\sigma$	Standard deviation
$\sigma_a$	Peak width factor, $\omega < \omega_p$
$\sigma_b$	Peak width factor, $\omega > \omega_p$
$\omega$	Wave frequency [ $\text{rad/s}$ ]
$\omega_e$	Encounter frequency [ $\text{rad/s}$ ]
$\omega_p$	Mean wave peak frequency [ $\text{rad/s}$ ]
$\nabla$	Volumetric displacement [ $\text{m}^3$ ]

## Acronyms

<b>ASW</b>	Anti-Submarine Warfare
<b>AWS</b>	Apparent Wind Speed
<b>CFRP</b>	Carbon Fiber Reinforced Polymer
<b>CG</b>	Center of Gravity
<b>CIC</b>	Combat Information Central
<b>ECR</b>	Engine Control Room
<b>ER</b>	Engine Room
<b>FMV</b>	Swedish Defence Materiel Administration
<b>FOI</b>	Swedish Defence Research Agency
<b>HSwMS</b>	His Swedish Majesty's Ship
<b>JONSWAP</b>	Joint North Sea Wave Project
<b>MCM</b>	Mine Countermeasures
<b>MII</b>	Motion Induced Interruption
<b>MIF</b>	Motion Induced Fatigue
<b>MSI</b>	Motion Sickness Incidence
<b>NAO</b>	Naval Air Operations
<b>PTO</b>	Percent Time Operable
<b>RAO</b>	Response Amplitude Operator
<b>RMS</b>	Root Mean Square
<b>SAR</b>	Search and Rescue
<b>SMHI</b>	Swedish Meteorological and Hydrological Institute
<b>SSA</b>	Single Significant Amplitude
<b>SUW</b>	Surface Warfare
<b>TAP</b>	Transit and Patrol
<b>TAS</b>	Towed Array Sonar
<b>VCG</b>	Vertical Center of Gravity
<b>VDS</b>	Variable Depth Sonar
<b>WRL</b>	Weapon Systems Reload



# 1 Introduction

FOI researches a variety of topics, mainly for the authorities within the Swedish total defence, among other things pre-studies for development of new systems, and performs evaluation of systems as basis for selection and to identify potential capability gaps. In the assessment of a ships performance in waves, which has implications on it's capability to perform missions, there are a few issues that this project aims to bring light to.

## 1.1 Background and Problem Description

The larger combat ships in the Swedish navy, which is not a blue water navy but one for littoral combat, are of an intermediate size that make them behave neither like small planing boats, nor like most big displacement ships, in terms of motion in waves. Therefore most traditional, platform dependent, criteria such as RMS roll and pitch angles might give inaccurate indication on performance. Instead platform independent criteria, explained in subsection 2.1, like MSI, Motion Induced Interruptions (MIIs), slamming and deck wetness should be used.

Furthermore, the tasks the crew on a naval ship have to perform in a critical situation can be a lot higher paced and with greater stakes, than the ones merchant vessel crews do. When crews have to be as alert and sharp as they do in this case, it might not be enough that they are not motion sick, the Motion Induced Fatigue (MIF) that can come before motion sickness might be enough to reduce crew performance to intolerable levels. Because of this, lower limits than usual on MSI could be motivated. Finally, if a merchant vessel can not operate in conditions that exist a few days a year, that means a slight reduction in the incomes per year, while a ship meant to defend against an invasion is worthless if the adversary is able, and chooses, to attack on such a day. This calls not only for an evaluation of the Percent Time Operable (PTO), but also of what missions and what weather is limiting it.

## 1.2 Scope and Objective

The project is meant to accomplish two main tasks. The first is to investigate what a reasonable limit on ship motions should be to make sure that the crew remains able to perform their duties and that all systems are working. The second task is to investigate the PTO at each mission of the Visby class corvette with regard to these limits, as well as the circumstances of the occasions where the ship fails with any of the criteria.

## 1.3 Methodology

The ship motions are studied primarily using existing software for strip theory, the commercial software

`Octopus Office 6` (ABB, 2008). The open source software `PDSTRIP` (Bertram, Veelo, Söding, & Graf, 2006) is used for some testing during the project, but not for producing any final results. Where desired functionality is lacking, the data is exported to perform the calculations in `Matlab`, developing scripts for this and verifying against results from `Octopus Office 6`.

The hull geometry that is evaluated is not the exact hull geometry of the Visby class corvettes. Instead, an approximation based on Fig A.1 in Appendix A is used. The effect of motion on a crew's physical and cognitive performance is studied through literature, to decide on a set of representative seakeeping criteria. Former commanding officers of Visby class corvettes are interviewed to know what factors are important to study. Relevant wave spectra are calculated from wave buoy data from the Swedish Meteorological and Hydrological Institute (SMHI).

## 1.4 The Visby Class Corvettes

The analysed ship will be the Visby class corvette, a lightweight stealth corvette in service within the Swedish navy (SAAB, 2020). It is very small for a corvette, right in the middle between the typical characteristics for a patrol craft and a corvette as can be seen in Tab 1, The classification of corvette is rather due to its capabilities and missions than its size. It is also very light due to its Carbon Fiber Reinforced Polymer (CFRP) construction.

**Table 1:** Typical parameters of naval vessels (Kapsenberg et al., 2015, and references therein) compared to the Visby class corvettes (in bold). For more parameters on the Visby class, see Appendix A

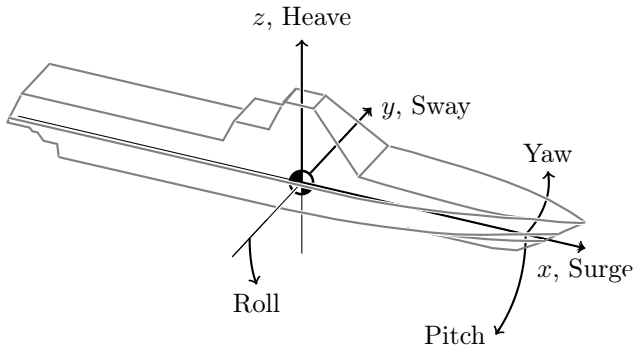
Type of ship	$L_{WL}$ [m]	$\nabla$ [m <sup>3</sup> ]	$v_{max}$	
			$\frac{Fn}{\sqrt{L_{WL}g}}$	$\frac{Fn_{\nabla}}{\sqrt[3]{\nabla}g}}$
Patrol craft	40	300	1.04	2.54
<b>Visby</b>	<b>62</b>	<b>636</b>	<b>0.73</b>	<b>1.96</b>
Corvette	85	1 800	0.53	1.41
Frigate	125	3 800	0.44	1.25
Destroyer	155	7 300	0.46	1.31
Cruiser	210	18 000	0.45	1.28

The Visby class corvettes' missions include Transit and Patrol (TAP), Anti-Submarine Warfare (ASW), Surface Warfare (SUW), Mine Countermeasures (MCM) and Search and Rescue (SAR) (Swedish Defence Materiel Administration, 2022). Three of the five ships also have a helipad and therefore the capacity for Naval Air Operations (NAO) (Swedish Armed Forces, 2021), and it was originally intended that they would have air defence capabilities although no surface to air

missiles has yet been acquired or installed, making the gun the only weapon for air defence. It is powered with a combination of gas turbines and diesel engines, depending on power requirements, driving twin water jets. To reduce roll in a seaway it is equipped with active stabilizing fins, (Backman, 2023) and has a thin plate keel running along the centerline, see Fig A.2 in Appendix A. The main particulars of the ship are also presented in that appendix.

## 1.5 Definition of Coordinate System

Where nothing else is explicitly stated, the coordinate system presented in Fig 1 is used in this report, with the origin for all axes in Center of Gravity (CG). That is, surge ( $\eta_1$ ) is positive forwards, sway ( $\eta_2$ ) is positive to port side, heave ( $\eta_3$ ) is positive upwards, roll ( $\eta_4$ ) is positive when heeling to starboard, pitch ( $\eta_5$ ) is positive when trimming on the bow, and yaw ( $\eta_6$ ) is positive when turning to port.



**Figure 1:** Axis orientations, origin in CG.

## 1.6 Limitations

**Testing:** No physical experiments are carried out, so this work is based entirely on existing literature, open source data, first hand sources and theoretical calculations.

**Confidentiality:** Some relevant literature is classified, and unavailable. This is also the case for several critical data about the ships. Furthermore there is a limit in how accurate inputs can be used before the results become sensitive information. Since this is an openly

published thesis, great care is taken to stay on the safe side of that limit. This of course has implications on the accuracy of the results, and therefore on the

**Statistical distribution of headings:** There are prevailing directions for waves and the wave directions are included in the used source of wave statistics (SMHI, n.d.), however the ship heading is unknown. Therefore it is generally assumed that all desired headings relative to the waves main direction are equally probable.

**Factors that do not relate to ship motion:** Conclusions are only drawn based on seakeeping behaviour. This project could for example conclude that ASW is possible in a very severe sea state if only the crew and necessary equipment can function as needed in the motions caused by that sea state. In reality something else might be limiting, like the under water noise from the waves might make it impossible to hear submarines. Neither is ice considered.

**Involuntary speed loss:** No calculations of wave resistance or propulsive effectiveness are done, and thereby any involuntary speed loss is disregarded.

**Active stabilization:** The Visby class corvettes are equipped with a pair of active stabilizing interceptors that make a great difference on the roll motions (Backman, 2023) and should also be able to adjust the ships trim, thereby possibly reducing the occurrence of slamming. Since the settings for the control system are unknown to the author, the interceptors are disregarded altogether.

**Loadcases:** Only the design waterline is considered, independent of mission. This gives a fixed displacement and longitudinal center of gravity, while the Vertical Center of Gravity (VCG) and the radii of gyration each take an estimated value to match results from inclination and roll decay tests. The trim and stability book does contain extensive information on the position and weights of all equipment for different armament options, but without going into details on what load case to use it makes little sense to input all these individual weights.

## 2 Theory

This chapter presents some different criteria that are relevant to the Visby class corvettes and some of the research aimed at identifying reasonable limits for ship motions. The JONSWAP wave spectrum used in the project is also presented.

### 2.1 Different Kinds of Seakeeping Criteria

Unless it is known for the ship in question, or a similar ship of a similar size, what magnitude of motions or accelerations that cause an unacceptable loss of performance, platform-independent criteria should be used. These are criteria relating to the limiting factors, rather than relating to a motion that in turn causes the limiting factors. Examples of platform-independent criteria are MSI index, MII index, slamming and deck wetness, while for example Single Significant Amplitude (SSA) of vertical acceleration is a platform-dependent criteria since the consequence of a vertical acceleration also depends on the frequency, which depends on ship size. (Graham, 1990; NATO STANAG 4154, 1997)

Platform-independent criteria can be further subdivided into quantitative and qualitative performance criteria. Here quantitative means that the effect on an absolute measure of performance can be quantified, like the velocity of the point of a gun affects the direction of the projectile (NATO STANAG 4154, 1997). This should however in many situations, like the one mentioned, make it possible to compensate for the motion as long as they are measured. Qualitative criteria on the other hand require empirical data to set limits, but the limits will be valid for different kinds and sizes of ships. MSI index is a common example.

In the ideal case a seakeeping analysis should be done with only platform-independent, quantitative criteria with clearly defined requirements. This is in reality rarely accomplished, which is why a mix is often used. (NATO STANAG 4154, 1997)

A final kind of criteria is rule based criteria, for example the Visby class corvettes are only classed to have helicopters land on them up to a certain significant wave height. This will then automatically be a criteria for NAO.

### 2.2 NATO Criteria for Ship Design

NATO has standardized common procedures for ship design, with regards to good seakeeping characteristics (NATO STANAG 4154, 1997). Table 2 below presents some of its seakeeping criteria often used in ship design, aimed at preventing the deterioration of crew safety and effectiveness (ABCD Working Group

on Human Performance at Sea, 1995; NATO STANAG 4154, 1997). Single Significant Amplitude (SSA) is the average of the top 1/3 quantile of amplitude and given the statistical distribution of wave heights, it is two times the standard deviation or RMS of instant values. It is used because it is a representative value of amplitude and close to what a trained observer would estimate (ABCD Working Group on Human Performance at Sea, 1995).

**Table 2:** Traditional seakeeping criteria for crew performance (Adopted from Pattison & Sheridan, 2004)

Recommended criteria	20 %	MSI in 4 h
	1	MII per min
	35 kn	AWS
Default criteria	8°	SSA roll
	3°	SSA pitch
	0.4 g	SSA vertical acceleration
	0.2 g	SSA lateral acceleration
	35 kn	AWS

Of these, the top three are platform independent and recommended by NATO STANAG 4154 (1997) to be used at each relevant task location onboard, for Apparent Wind Speed (AWS) that is the helicopter pad or other task locations on weather deck, and the others should be used if necessary. Also in the standard, are criteria and limits relating to the ship itself, like slamming, propeller emergence and deck wetness, and criteria relating to the performance of different subsystems and task specific working locations. The latter two are organized by the type of mission, such as ASW, NAO, WRL, MCM etc.

### 2.3 Motion Effects on Human Performance

The effects of motions on human performance can be classified into pure motion effects on performance, MIIs, and effects on cognitive performance. Cognitive performance refers to the ability to solve cognitive tasks, which could also be divided into purely cognitive, psychomotor, and visual tasks.

The closest thing available to a measure on degradation of cognitive performance is MSI index, which is the percent of people that throw up during a given reference period of exposure to the motion, it has been determined as an empirical function of vertical accelerations and frequency of motion. Only motions of a frequency of 1 Hz or less cause MSI. On passenger ships the comfort onboard is very important, and MSI index is then a good measure of the performance in that matter, but on naval ships things are different. Here comfort is not so much of a goal in itself, but it has

implications on performance, which is the main goal. It could then be questioned if MSI is a platform independent criteria for naval ships, but it is still the best available, the following paragraphs present some research on the connection between motion sickness and cognitive performance.

A study where subjects were tested on their abilities to perform naval shipboard tasks while experiencing motions replicating those on a frigate in severe weather for around 90 minutes (Conwell Holcombe & Holcombe, 1996), concluded that purely cognitive abilities were hardly affected, at least in that short time span. Visual and psychomotor abilities were however hampered, with the subjects taking longer time to solve tasks and still making mistakes. About 20 % of subjects reported Motion Sickness Incidences (MSIs), meaning that they vomited, and of those a majority chose to abort the test due to MSIs. This means that the amplitude and frequency of the accelerations were likely corresponding to 20 % MSI index. The conclusion made by the authors, that the cognitive performance was not hampered much, is an indication that the 20 % MSI criterion in Tab 2 are safe.

Another later study (Matsangas, McCauley, & Becker, 2014), saw performance decline even from mild motion sickness. In this study a group of mostly active duty military officers, with a lower average susceptibility to motion sickness than the general population, were tested on cognitive multitasking performance under gentler motions. It also concluded that this performance decrease could be countered by increasing the focus on the task at hand, which means that the more motivated the crew is, the less its performance degrades. In a serious situation, navy personnel will undoubtedly be highly motivated, the same might not be true for an everyday situation that without much warning is about to turn serious.

## 2.4 Motion Induced Interruptions

A Motion Induced Interruption (MII) is an event where a person stumbles, slips or is forced to take action to prevent it, due to the motions of the ship. Treating the person as a rigid body, there are simple calculations to find these events (Crossland & Rich, 2000). These are explained below. The most simple example of this phenomena, which is familiar to most people, is trying to stand up without bracing oneself in a subway, tram or similar. In contrast to a ship in waves the tram moves mostly in one degree of freedom, surge ( $\eta_1$ ), and has constant vertical acceleration  $\dot{\eta}_3 - g$ . What one does to keep the balance is to stand sideways with a wide stance, because when the tram accelerates the tipping moment must not exceed the righting moment. Otherwise the person must take a step or stumble, i.e. a Motion Induced Interruption. Since  $\eta_5$  can be assumed to be small  $\cos(\eta_5) \approx 1$  and  $\sin(\eta_5) \approx \eta_5$ . In conclu-

sion, an MII occurs if

$$h(\ddot{s}_1 - \eta_5 g) > l(\ddot{s}_3 + g) \quad (1)$$

or

$$h(-\ddot{s}_1 + \eta_5 g) > l(\ddot{s}_3 + g) \quad (2)$$

The ratio between the half stance width and the height of the center of gravity,  $l/h$ , is called the tipping coefficient. An MII can also occur due to slipping, if the frictional coefficient  $C_f$  is exceeded by the ratio between lateral and downwards acceleration.

$$\ddot{s}_1 - \eta_5 g > C_f(\ddot{s}_3 + g) \quad (3)$$

or

$$-\ddot{s}_1 + \eta_5 g > C_f(\ddot{s}_3 + g) \quad (4)$$

The two expressions each represent stumbling either one way or the other. At a later stage they can be combined into something that represents stumbling regardless of direction.

The commuter will also know that the tram sooner or later turns, causing a centrifugal acceleration in the sway direction,  $\ddot{\eta}_2 \neq 0$ . Even if  $\ddot{\eta}_2$  is much smaller than  $\ddot{\eta}_1$  can be, it can cause an MII for a person standing sideways since  $l$  is then only half the length of the persons foot. This shows how the tipping coefficient is dependent on the persons orientation and that another variant of definitions (1) and (2) is just as valid, and in fact more relevant in seakeeping (Crossland & Rich, 2000) since roll motion usually causes transverse acceleration to be dominant over longitudinal acceleration. Graham, Baitis, and Meyers (1992) also introduces the effect of wind on MII but the relevant locations considered in this report are all indoors.

The roll acceleration also introduces a new term relating to the persons rotational inertia, the term  $\frac{h}{3}\ddot{\eta}_4$ , the persons radius of gyration around a horizontal axis is assumed to be  $h/3$ . With this addition the formulation for MIIs as given by Crossland and Rich (2000) is obtained.

$$h\left(-\frac{h}{3}\ddot{\eta}_4 + \ddot{s}_2 + \eta_4 g\right) > l(\ddot{s}_3 + g) \quad (5)$$

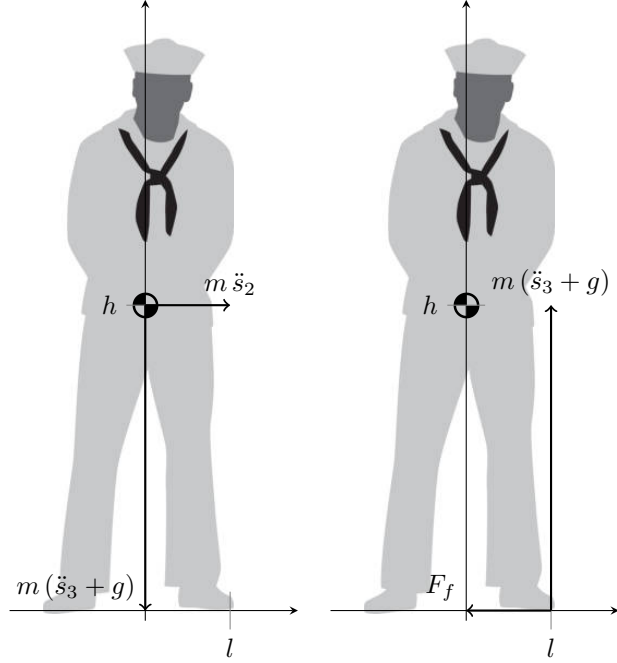
or

$$h\left(\frac{h}{3}\ddot{\eta}_4 - \ddot{s}_2 - \eta_4 g\right) > l(\ddot{s}_3 + g) \quad (6)$$

One note here is that the small roll angle assumption is questionable, it is however necessary to have linear behavior, both for strip theory for probabilistic calculations with MII.

Figure 2 shows a sailor on the verge of tipping sideways, since an increase in  $\ddot{s}_2$  or decrease in  $\ddot{s}_3$  would shift the balance of the moments, for example around the point  $(l, 0)$ . As can be seen in the figure, the left and right hand sides in one of expressions (5) or (6) are

equal. Also if  $F_f = C_f m (\ddot{s}_3 + g)$  the sailor is on the limit for a sliding MII since  $F_f$  cannot increase with  $\ddot{s}_2$  anymore. In this case the left and right hand sides in one of expressions (3) or (4) are also equal.



(a) Apparent forces from accelerations.

(b) Forces from the deck contact.

**Figure 2:** Forces acting on a person at the limit for a MII, the figure assumes  $\eta_4, \ddot{\eta}_4 = 0$ . With the following symbols:

$$\begin{aligned} F_f \leq C_f m (\ddot{s}_3 + g) & : \text{ Friction force} \\ m & : \text{ Mass of person} \end{aligned}$$

Criteria for MII are set to a certain rate of MII events,  $\dot{N}_{\text{MII}}$ , determined by the probability at each wave encounter, and with the appropriate tipping- or frictional coefficients depending on the conditions for the task, like person orientation, working posture, and deck surface. The allowed rate is usually determined by the consequence of a fall, for example if a person could

fall overboard or otherwise be harmed, or by the extra time required to finish a task at hand when getting interrupted to keep the balance.

## 2.5 The JONSWAP Wave Spectrum

The different sea states will for calculations in the frequency domain be represented by sea spectra. They are characterized by a significant wave height, a time period, spreading, and sometimes other shape factors. In the Swedish waters, where the Visby class corvettes are mainly meant to operate, the waves have very limited fetch. For these conditions the Joint North Sea Wave Project (JONSWAP) sea spectrum is the most reasonable choice of standard spectrum (Mitchel, 1999), it can be calculated from the formula

$$\begin{aligned} S^\zeta(\omega) &= a g^2 \omega^{-5} e^{-\frac{5}{4} \left(\frac{\omega_p}{\omega}\right)^4} \cdot \gamma^r \\ r &= e^{-\frac{(\omega - \omega_p)^2}{2 \sigma^2 \omega_p^2}} \end{aligned} \quad (7)$$

The parameter values are defined by Schreuder (2014)

In order to make the sea short crested, like a natural sea state built by wind, the spectrum is multiplied by the spreading function  $D$  which is most commonly defined as following

$$\begin{aligned} S^\zeta(\omega, \theta) &= S^\zeta(\omega) D(\theta) \\ D(\theta) &= \begin{cases} \frac{2}{\pi} \cos^2 \theta, & \text{if } |\theta| < \frac{\pi}{2} \\ 0 & \text{otherwise} \end{cases} \end{aligned} \quad (8)$$

However, if the ship has non-zero speed then for all the wave components that are other than perfect beam seas, the encounter frequency  $\omega_e$  will differ from the wave frequency  $\omega$

$$\omega_e = \omega - \frac{\omega^2}{g} v \cos(\mu + \theta) \quad (9)$$

which means that the sea spectrum has to be modified into the encounter sea spectrum

$$S_e^\zeta(\omega_e, \theta) = \frac{S^\zeta(\omega, \theta)}{1 - \frac{2\omega}{g} v \cos(\mu + \theta)} \quad (10)$$



### 3 Method

This chapter presents the criteria and weather data that are chosen for performing the calculations, and how `Octopus Office 6` is set up. `Octopus Office 6` is used for calculating the Response Amplitude Operators (RAOs) with linear strip theory. To perform the operability study, and get numbers on Percent Time Operable (PTO), the complex transfer functions, or RAOs are exported to `Matlab`, where they are stored as complex numbers. The response calculations are then automated in `Matlab` to allow a higher resolution of sea states.

#### 3.1 Selecting Criteria

The Visby class corvettes are built to last through rough weather, and former commanding officers Backman (2023); Öhrstedt (2023) are convinced that man and not machine is limiting. It is therefore natural to have a focus on criteria that quantify the motion effect on human performance, such as MSI index and MII index.

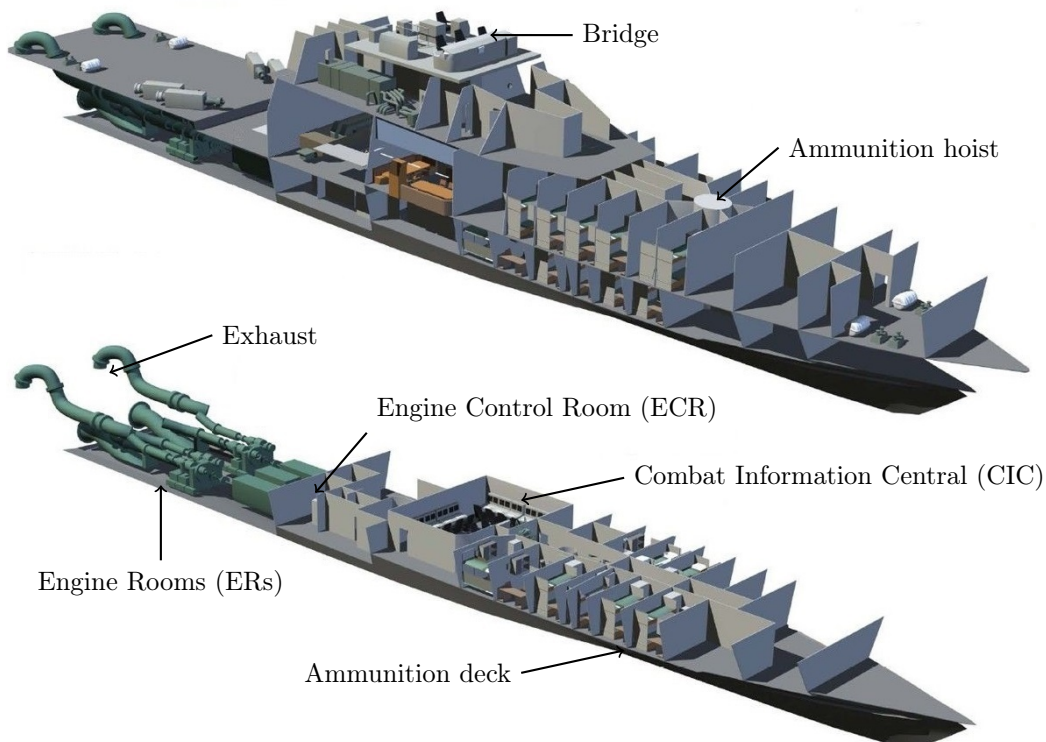
Here MSIs is used in locations where cognitive, visual, and psychomotor tasks are performed, this includes the bridge, the ECR and the CIC, see Fig 3 below. In these working stations the crew are seated in chairs offering good support, so MIIs are less of an issue.

MIIs are instead used in locations where manual work

is performed, when it comes to manual work that can be urgent and not wait until calmer conditions, this is mostly the ERs and the ammunition deck. Criteria for MII in the ERs are set for missions where it's assumed that a certain combination of speed and heading could be strongly required, making temporary adjustments unviable in the situation when urgent work is required there. On the ammunition deck MII criteria are of course used for Weapon Systems Reload (WRL), and also for SUW where the gun is used for self defence against anti-ship missiles. Sohlin (2023) says the gun should always be reloaded as it is fired, by crew on the ammunition deck, to have maximum freedom of choices.

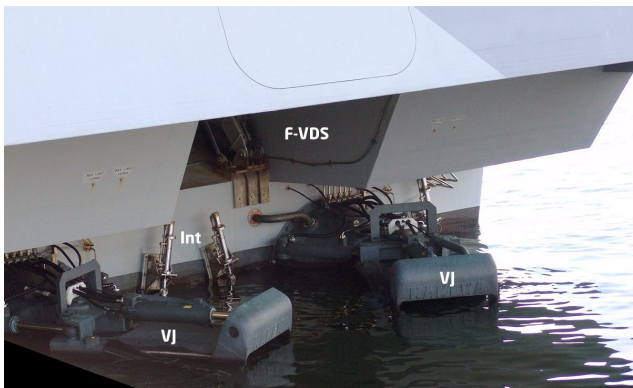
As previously established, since transverse accelerations are dominating on displacement ships, Crossland and Rich (2000) recommend only using MIIs from accelerations in the transverse direction, and not longitudinal. Slipping MIIs are not relevant in working stations indoors where the deck is dry and has a lot higher friction coefficient to a shoe sole than the tipping coefficient could possibly be.

Green water on deck is a commonly used platform independent criteria, but is not considered since it, in itself, is not a problem on a ship where all important equipment is protected behind hatches, and the deck is not a working station. In addition the freeboard on the Visby class corvettes is very high (Backman, 2023).



**Figure 3:** 3D-model of the interior (adopted from Städje, 2014a). Locations considered for human performance are marked out.

Another common platform independent criteria, propeller emergence can also be disregarded since the Visby class corvettes are propelled by water jets, and the risk of their intakes ventilating can safely be disregarded. Whether the water jet nozzles themselves stay submerged does not affect performance a lot (Backman, 2023), and the strip theory used in this project is not suitable for evaluating the surface level aft of the transom. At zero speed the water jets are located below the water surface, see Fig 4 where they are marked as “VJ”.



**Figure 4:** Opening to cargo deck where the Variable Depth Sonar (VDS) is located (adopted from Stådje, 2014b).

What could be an issue is submergence of the underside of the stern overhang, where the gas turbine exhausts are located, too much water in them could be problematic (Backman, 2023). There is also an opening there, to a confined part of the cargo deck, see Fig 4, but this place is often sprayed by the water jets according to Stådje (2014b), and it can be assumed that a wave crest could not do damage there if the water jets do not. Submergence of the gas turbine exhausts is again behind the transom and so cannot be accurately evaluated at speed, however the waves radiating from the moving ship, that cause the inaccuracies here, should work in the vessels favour and make submergence much less likely. Therefore submergence of the exhaust is only considered at zero speed.

In Tab 2 AWS is also recommended, however the sea state data lacks any information about wind, which complicates the use of it as a criterion. The formula for the JONSWAP spectrum does have a physical connection to wind speed, but it is also dependent on geography, so to calculate the wind speed from a given sea state, the location and heading have to be considered, adding dimensions to the matrix of sea states to cycle through.

The sides of the hull and superstructure above the line of maximum beam slope inwards about  $15^\circ$  from vertical, consequently the ship will be significantly more

visible on radar from the beam direction when the roll angle is  $15^\circ$ . Therefore an SSA roll angle of  $15^\circ$  is a justified criterion for a ship which has a survival strategy based on not being detected. Also such a large roll angle would probably cause larger problems onboard, after all it is close to twice as high as the  $8^\circ$  SSA roll advised by (NATO STANAG 4154, 1997), see Tab 2. It is however unlikely that an enemy radar antenna would be directed straight at the ship, from the right narrow angle, in the exact instance that the roll angle is just right. In addition to that the sea state required to cause such a heel angle would also cause a significant amount of radar clutter (radar echos from waves) to hide in.

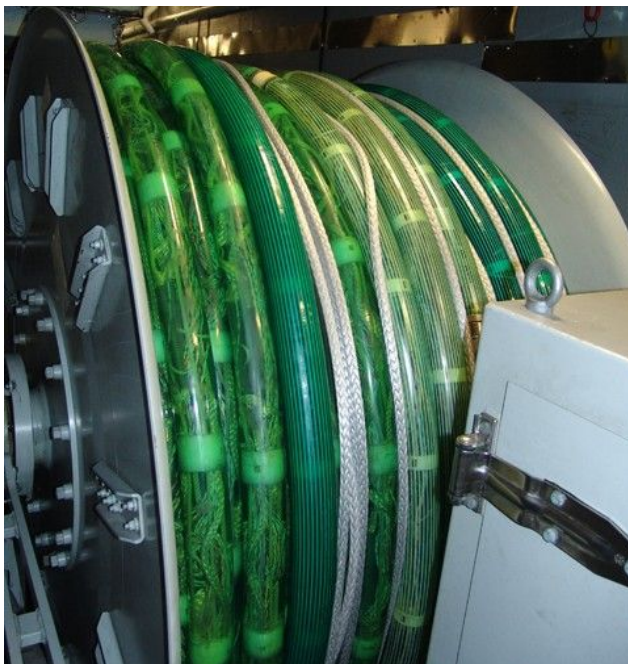
Roll angle is also relevant when firing anti-ship missiles, they are launched out the side of the vessel and are not allowed to hit the water. After their launch has been ordered they are held until the momentary roll angle is within an allowed window, then they are fired automatically (Backman, 2023). Since it can be important that the missiles reach their target as soon as possible, it would not be acceptable to have their launch delayed for too long, which could motivate a limit on the combination of large SSA roll and long zero crossing periods on the roll response. The limits of this window is typically classified though (NATO STANAG 4154, 1997), making it hard to set a valid limit, in that amplitude and period combination.

Surfing/broaching, parametric roll and synchronous roll is considered as criteria for qualitative analysis of the responses in certain sea states but not for calculations of PTO, they are automatically tested for in *Octopus Office 6* but their results cannot be exported. Slamming will also be considered, not for structural issues, HSwMS Visby has built in strain sensors in the hull that never show problematic numbers (Öhrstedt, 2023), but for the sake of the crew. The very stiff CFRP hulls make slamming very uncomfortable (Backman, 2023) and could be bad for both health and performance. This would also increase the damaging potential of slamming on other systems like antennas.

There are well developed criteria for Naval Air Operations (NAO) for all kinds of aircraft, developed for much larger vessels (NATO STANAG 4154, 1997). Since NAO is not one of the main missions of the Visby class corvettes and since their class certificate allows helicopter operations up to a certain significant wave height, that criterion will be used for NAO. The gun accuracy is not limiting because of its sophisticated gyro stabilization that is built to compensate for ship motions (Backman, 2023; BAE Systems Bofors, 2016). Radars are also gyro stabilized and are typically very insensitive to heel angles, and are therefore very unlikely to be limiting (Backman, 2023). No criteria for replenishment at sea will be considered since the

Swedish navy rarely operate far from sheltered waters.

The hull mounted sonar is not placed in a bulbous bow-like dome, like on many larger naval ships, but further aft, and is not going to emerge due to ship motions (Backman, 2023). Towed equipment are typically designed with enough compliance to cope with ship motions up to the level where other aspects on the ship are limiting, and towing techniques can be adapted to minimize influence of ship motion on the performance of the equipment (NATO STANAG 4154, 1997). The Towed Array Sonar (TAS) deployed by the Visby class corvettes is a long flexible tube, see Fig 5, and quite easy to deploy and retrieve, (Backman, 2023) so this will not be regarded as limiting.



**Figure 5:** The Towed Array Sonar (TAS) (adopted from Stadje, 2014b).

The VDS is deployed by winching it down between the water jet propulsors, when retrieving it large motions

can be a problem. There are however rules for when the TAS and VDS are allowed to be deployed. When deployed the cable to the VDS is automatically adjusted to compensate for vertical motions and allow the sonar to stay at a constant depth.

### 3.2 Selecting Levels for Criteria

Table 3 presents all the criteria that are chosen based on the reasoning in subsection 3.1. An empty cell means that the criterion is not necessary for the mission. The chosen levels are motivated below.

For Motion Sickness Incidence, 20 % during a four hours reference period is a widely accepted limit, although not fully supported by evidence (NATO STANAG 4154, 1997). The reference period of four hours comes from people taking some time to start getting sea sick, and later becoming habituated, after about four hours from the start of the motions, it is at its worst point (Riola, Esteban, Giron-Sierra, & Aranda, 2004).

Based on the reasoning in subsection 2.3 the MSI limit is set lower for TAP during which the crew can be assumed to be less motivated and possibly more prone to MIF, compared to for example combat missions. It is for example reasonable to assume that at a given level of motion sickness a crew member would be completely able to detect a threat when threats are expected, but could fail to detect the threat if all that is expected is more hours of being sea sick and bored. Therefore the decided limits are 20 % for TAP and 30 % for other missions. It is also an opinion expressed by Orstedt (2023) that motion sickness is less of an issue in serious situations.

These limits are set in the approximate locations of the bridge, the ECR, and the CIC, for all missions with two exceptions. The bridge is assumed to have little significance to the WRL activity, and crew performance in the Engine Control Room during TAP missions is assumed to only be critical if something unexpected happens in the engine room. It is then assumed that the

**Table 3:** Limit values of the chosen seakeeping criteria.

Mission/ activity	Criteria								
	SSA roll & pitch	MSI bridge	MSI CIC	MSI ECR	Slam- ming bow	Submer- gence stern	MII ammu- nition deck $l/h = .170$	MII ER $l/h = .222$	$H_s$
TAP		20 %	20 %	30 %	20 /h	0.25 /h			
SUW	7.5°	30 %	30 %	30 %	40 /h	0.25 /h	60 /h	60 /h	
ASW	7.5°	30 %	30 %	30 %	40 /h	0.25 /h		60 /h	
MCM		30 %	30 %	30 %	40 /h	0.25 /h		60 /h	
SAR		30 %	30 %	30 %	40 /h	0.25 /h		60 /h	
NAO		30 %	30 %	30 %	40 /h	0.25 /h		60 /h	4 m
WRL			30 %	30 %	40 /h	0.25 /h	60 /h		

alarms would be able to alert the crew there so that they could be motivated enough to handle any task despite being motion sick. On the bridge and in the CIC on the other hand, it is assumed that some problems are only first identified by an alert human, and not a sensor.

The tipping Coefficients for MII are taken as recommended by Crossland and Rich (2000) and are based on physical experiments in a large motion simulator. For the Engine Room the average recommended coefficient for all tasks was chosen, since there is a wide variety of tasks and working positions in an engine room. For the ammunition deck the recommended coefficient for the loading task was chosen. The chosen limit for the rate of MIIs is one per minute, as suggested by NATO STANAG 4154 (1997).

On the ammunition deck, the limit can be checked using the method for setting limits based on requirements on task effectiveness described by Crossland and Rich (2000). It states that the criterion for the allowed rate of MIIs is

$$\dot{N}_{\text{MII}} = \left( \frac{1 - E_{\text{task}}}{D_{\text{MII}}} \right) \cdot 3600$$

where the MII duration  $D_{\text{MII}}$  can be taken as the mean from the tests by Crossland and Rich (2000), 3.57 s. The task effectiveness  $E_{\text{task}}$  is the ratio between the maximum allowed time it can take to perform the task, and time it takes without the detrimental effect of ship motion.

With one MII per minute the task effectiveness is approximately 0.94 from this the performance of the gun can be estimated from data on the system. In its automatic loading system the gun stores 140 rounds that can be fired without manual work, and these can be fired at a rate of 220 rounds per minute (Sohlin, 2023). Although the gun is not operating in such a way that all rounds are fired in continuous automatic fire and the 140 rounds are distributed over different magazines (Sohlin, 2023), therefore the rate of consumption is lower than the rate of fire. For an estimation of the actual rate of consumption it could be estimated that each target is serviced by five shots like in a video showing a demonstration of the air defence capability on the website of Swedish Defence Materiel Administration (2022). If it is then assumed to take half a second between firing on different targets the rate of consumption drops to 161 rounds per minute.

The rest of the ammunition is supplied to the turret through two ammunition hoists, one on either side, each capable of supplying 60 rounds per minute (Sohlin, 2023). The bottleneck is however the crew members on the ammunition deck who load a 13 kg pair of rounds at a time into their respective ammunition hoist and then push a button, something Sohlin

(2023) estimates takes a maximum of ten seconds, but faster with preparation or two crew members cooperating. At time stamp 4:00 in a YouTube video by Military Channel J (2022) this sequence is shown with one man comfortably performing a cycle in what appears to be about six seconds, here the workstation is prepared, with the rounds close to the ammunition hoist. Using this figure means that around 40 rounds per minute make it to the turret if both hoists are operating in calm weather, with a task efficiency of 0.94 it drops down to 37.6.

With a rate of consumption of 161 rounds per minute, 140 rounds are fired in 52 seconds, with a reload rate of 40 rounds per minute the ammunition runs out after 69 seconds, and a total of 186 rounds will have been fired. At the decided limit on rate of MIIs with a reload rate of 37.6, 182 rounds can still be fired before the ammunition runs out after 68 seconds. This small difference is most likely acceptable.

On slamming, the limit of 20 instances per hour is taken, as recommended by NATO STANAG 4154 (1997) for TAP. This despite the fact that this limit is based on structural considerations, and it was established in subsection 3.1 that the main issue with slamming on the Visby class corvettes is the well-being of the crew. The limit is still reasonable, it is the same magnitude as the limit set on MIIs and slightly lower than a risk level for MII called “probable” by Crossland and Rich (2000), and slamming has some similar consequences to MIIs, on people. For example it can cause a forwards tipping MII, by causing negative accelerations in pitch and surge that are not picked up by linear strip theory, where unlike in reality, slamming is only a consequence and never a cause of motions.

Like with MSI it is reasonable to demand from the crew that they endure more in a more dire situation, which is why the limit for the other criteria is set to 40 slamming events per hour. This number is somewhat arbitrary, but comes from the reasoning above that the ship is strong enough to withstand the loads from slamming, and this number is closer to the limit on MIIs. The effect of this decision will also be evaluated.

When it comes to SSA roll, the 15° previously mentioned are likely too high meaning both that its compliance will not ensure safe or effective operations, and that it will never be the limiting criterion. For example it would cause an MII even at  $l/h = 0.26$  and with no accelerations, see the  $\eta_4$  term in definition (5).

On the other side of the spectrum are the limits recommended by NATO STANAG 4154 (1997), 15° again for hull mounted sonar performance and 7.5° for gun accuracy as well as torpedo and missile launch, they apply to both roll and pitch. The gun used in the tests that gave this limit was older and larger with a 5" caliber

though, compared to the 57 mm gun on the Visby class corvettes, an older and larger piece could be slower to stabilize than a new one. At the same time Backman (2023) does not see the launching of the light torpedoes as restricted by roll, but recognizes that it can be an issue for heavy torpedoes, which could be the source of the limit.

These limits are however frequency dependent, and over all intended for larger vessels. A smaller vessel typically has higher dominating frequencies of motion than a larger vessel in the same sea state, and as will be shown in subsection 3.5 the Baltic sea has unusually high wave frequencies compared to the open ocean. The more modern and nimble weapon systems point to selecting a higher limit while the higher frequency of ship motions indicate that a lower limit might be more accurate. If these inaccuracies are assumed to cancel out the limits for weapon systems from NATO STANAG 4154 (1997) can be used as they are more conservative than the limit based on slope angle of the sides.

### 3.3 Coordinates for Point Responses

While on open water, which is the only time relevant for a seakeeping analysis, the bridge is typically only manned by the navigation officer, who is seated in the chair on the center line. Meanwhile the work station of the commanding officer is down in the CIC (Städje, 2014a). This fortunately means that the roll motion will not contribute to the vertical accelerations that cause sea sickness for the navigation officer. There are of course exceptions, such as during SAR missions, when the global maritime distress safety system operator is stationed at a console further aft on the port side of the bridge, this will however be ignored in this analysis. From the general arrangement drawing, Fig A.2 in appendix A it can be estimated that the longitudinal position of the navigation officer's seat is 30.5 m, the vertical position is not relevant to vertical accelerations, the foundation of the MSI index.

The CIC, marked in light blue in Fig A.2 in appendix A, is unsymmetrical, but spans both sides of the center line. Since MSI is a statistical measurement the location should be Representative for the group of seats, but should also not underestimate the most severe motions too much. For this reason the chosen location is in the forward end of the room, sideways centered in it, the longitudinal position is about 34 m and the transverse position is 0.4 m to the port side. That the CIC is located forwards of the bridge makes it unlikely for motion sickness on the bridge to be limiting, but it is not impossible for all headings, so the bridge criteria is kept. The ECR is located aft of the CIC on the starboard side, see Fig 3, the representing position is taken as 24.5 m forwards of the aft perpendicular and 3.5 m starboard of the center line.

For slamming the longitudinal position should be far forwards but not so far that the bottom is too sharply V-shaped as it will cut through the wave without slamming. The longitudinal position of the point analysed is 55 m The point for evaluating submergence of the stern is the gas turbine exhausts, approximately 4.5 m aft of the aft perpendicular, 4 m from the center line on both sides and 3 m above the still water surface. To capture the symmetry behaviour the probability or rate of immersion for a given heading angle should be added with that for the opposite or negative heading angle. It can be done since both the ship and sea state spectra are symmetrical.

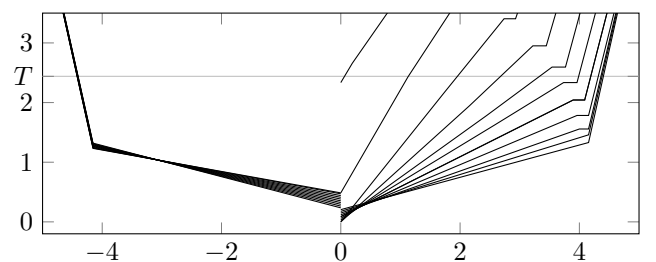
The ammunition hoist is located at the center line about 46.5 m forwards of the aft perpendicular. For the purpose of MII calculations the crew manning it is assumed to be 1 m above the keel line. The longitudinal position of work in the engine rooms is conservatively taken as 4 m, the transverse position as 3 m on either side, and the vertical position as 2 m. Table 4 collects all the above mentioned coordinates.

**Table 4:** Coordinates of Point Responses

Location	x	y	z
Bridge	30.5	0	
CIC	34	0.4	
ECR	24.5	-3.5	
Slamming point	55	0	0
Exhaust	-4.5	±4	5.4
ammunition deck	46.5	0	1
Engine room	4	±3	2

### 3.4 Analysed Hull Shape

For reasons of confidentiality mentioned earlier all calculations are done on a hull shape that is only measured from an openly published blueprint with poor resolution and wrong aspect ratio of the image, shown in Fig A.1 in Appendix A. This means that the hull shape is inaccurate, see the limitations in the introduction. Figure 6 shows the retrieved hull lines used in the simulations. A more scaled up version is found in Appendix A.



**Figure 6:** Lines plan of the underwater body that is used in the calculations.

**Table 5:** Source wave buoys.

Wave bouy name	Dates of recordings (UTC)	Location
Brofjorden WR boj	2017-02-08 09:00 - 2023-05-22 00:00	N 58.2513° E 011.2229°, Skagerrak
Väderöarna WR boj	2005-03-02 16:00 - 2023-05-22 00:00	N 58.4833° E 010.9333°, Skagerrak
Läsö ost boj	2001-05-08 09:00 - 2009-02-14 11:00	N 57.2164° E 011.5642°, Kattegat
Knolls Grund boj	2011-11-19 15:00 - 2023-05-22 00:00	N 57.5167° E 017.6167°, Sea of Gotland
Huvudskär ost boj	2001-05-10 22:00 - 2023-05-22 00:00	N 58.9333° E 019.1667°, Baltic sea
Svenska Björn boj	1982-11-01 04:00 - 1986-11-27 10:00	N 59.4662° E 020.3462°, Baltic sea
Finngrundet WR boj	2006-06-02 16:00 - 2023-05-22 00:00	N 60.9000° E 018.6167°, Bothnian sea

### 3.5 Sea States

The Swedish Meteorological and Hydrological Institute (SMHI) has a number of wave buoys around the Swedish coast, five of which are active in 2023. Historical data such as the 30 minutes significant wave height, mean peak period and mean direction can be downloaded from their website from both active and previously active wave buoys (SMHI, n.d.). Table 5 shows the wave buoys used in the operability assessment in this project. The recordings start and end at different times of the year, and there are some gaps in them, so they are not evenly distributed over the seasons. In total 22.1 % of the recordings are from the winter months, 22.6 % are from spring, 28.2 % are from summer, and 27.1 % are from autumn.

The sea states recorded by the wave buoys are for the purpose of calculating the PTO put in bins with a width of 0.1 meter significant wave height and 0.2 second peak period. The statistical distribution of all the recorded sea states from all wave buoys and all the months of the year is visualised in two ways in Fig 7. It is clear that even though there are recordings of high seas, the lower ones are dominating. Figure 7a also shows a peculiar shape with a hump that poorly matches probability distribution functions of common distributions, this hump is apparent over a range of bin widths in the  $T_p$  direction.

The count of each histogram bin is used for calculating the probability of the sea state in its center, for the purpose of evaluating PTO. In total 2 642 bins contain at least one recording, and will thus be used in the calculations. In a way this approach mimics a Monte Carlo simulation in that it uses almost half a million random sea states, only that they have been lumped together to reduce the computational burden.

Something worth noting is the apparent vertical lines in Fig 7b, an indication that at least some of the wave buoys round  $T_p$  to a lesser precision than the bin width. This means that the precision of the sea state probability data is not as good as it appears, but that is only an issue if there are large differences in responses with small changes in sea state.

For simplicity all sea states are assumed to have the

same spreading, with the spreading exponent 2 in the spreading function, equation (8). This gives a short crested sea that well mimics real wind generated waves. Two simultaneous sea states with different directions is not used since this is mostly for the situation when old swell and new wind generated waves meet, and the Baltic sea is too small to have particularly old swell. Only 2 % of peak periods measure over 10 s.

### 3.6 Settings in Octopus Office 6

The water depth at which the hydrodynamic coefficients are calculated is set to 70 m, this is greater than the average depth of the Baltic Sea, but somewhat representative for the locations of the buoys in Tab 5. The Keil solution method, suitable for shallow water is selected for evaluating the hydrodynamic coefficients.

The RAOs are determined for encounter frequencies corresponding to wave frequencies in the interval from 0.075 to 3.45 rad/s in steps of 0.075 rad/s, at speeds from 0 to 15 kn in steps of 3 kn, as well as 25 kn and 35 kn, and at headings in steps of 10°. With the way **Octopus Office 6** calculates RAOs, for a fixed set of wave frequencies instead of encounter frequencies, the response spectra are obtained simply by multiplying with the unmodified, spread wave spectra from equation (8), the calculations from equations (9) and (10) are already done in **Octopus Office 6**.

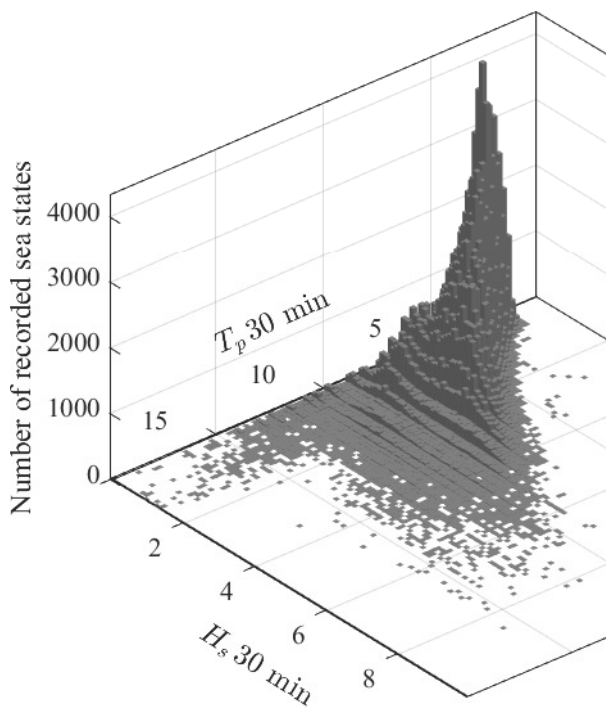
The same metacentric height is used as during the inclining test of HSwMS Visby, by ThyssenKrupp Marine Systems Kockums (2012). Because of the inaccuracies in the hull shape, most notably a slight difference in width, this gives the wrong VCG, but the metacentric height was considered more important. Free surface moments are taken as for the heaviest load case, 167.6 ton-m (ThyssenKrupp Marine Systems Kockums, 2012). The roll radius of gyration was initially taken the same as during roll decay test of HSwMS Visby, by ThyssenKrupp Marine Systems Kockums (2012) but is modified to give the same natural roll period as was recorded during that roll decay test, however the radius was still within reasonable limits with regard to the height and width of the ship. The other Radii of gyration are approximated entirely based on the length.

For roll damping the built in “Ikeda” method is selected, it is described by Journée and Adegeest (2003). Stabilizing fins are disregarded, the center line keel is approximated by the bilge keel option, with height 0.5 m and running the approximately the same length as the centerline keel is visible in in Fig A.2 in appendix A. This might be exaggerated, since bilge keels come in pairs, and the single keel on the Visby class corvettes decreases in height forwards, but on the other hand the roll damping from the fin stabilizers is lost. Hopefully these two inaccuracies somewhat cancel each other. Also the `Octopus Office 6` User Manual recommends tuning roll motion to fit test results, using the bilge keel height (Amarcon, 2010).

### 3.7 Implementation of Motion Induced Interruptions in Octopus Office 6

Despite MII being a recommended criterion by multiple sources (Crossland & Rich, 2000; Graham, 1990; NATO STANAG 4154, 1997; Pattison & Sheridan, 2004) etc. `Octopus Office 6` does not have it as a built in criterion. It can however be handled by the software as a custom criterion, with its RAO defined as a linear combination of other RAOs. Definitions (5) and (6) are then rewritten, isolating the tipping coefficient on one side, an MII happens if

$$-\frac{h}{3g} \ddot{\eta}_4 + \frac{1}{g} \ddot{s}_2 + \eta_4 - \frac{l}{hg} \ddot{s}_3 > \frac{l}{h} \quad (11)$$



(a) Histogram of sea states, obs axis directions.

or

$$\frac{h}{3g} \ddot{\eta}_4 - \frac{1}{g} \ddot{s}_2 - \eta_4 - \frac{l}{hg} \ddot{s}_3 > \frac{l}{h} \quad (12)$$

Therefore the RAOs for MIIs are, with the tipping coefficient as limit:

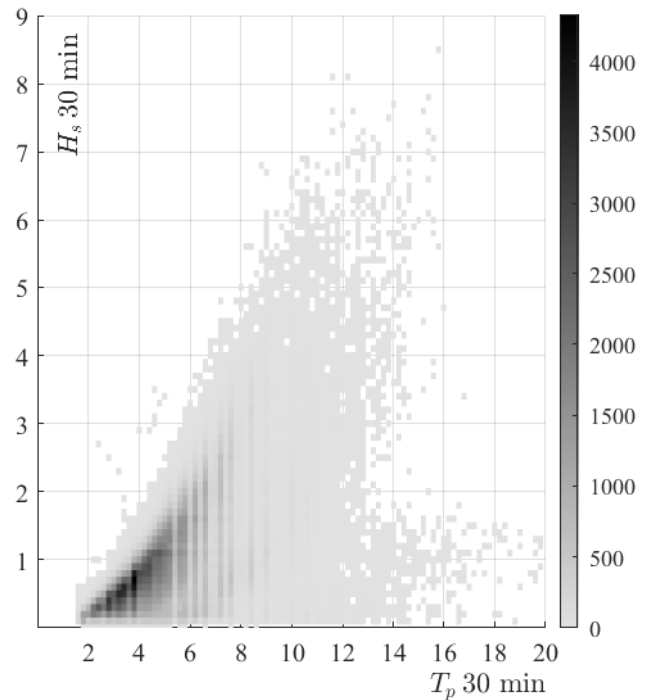
$$\begin{aligned} \text{RAO}_{\text{MII}} = \dots \\ -\frac{h}{3g} \text{RAO}_{\ddot{\eta}_4} + \frac{1}{g} \text{RAO}_{\ddot{s}_2} + \text{RAO}_{\eta_4} - \frac{l}{hg} \text{RAO}_{\ddot{s}_3} \end{aligned} \quad (13)$$

and

$$\begin{aligned} \text{RAO}_{\text{MII}} = \dots \\ \frac{h}{3g} \text{RAO}_{\ddot{\eta}_4} - \frac{1}{g} \text{RAO}_{\ddot{s}_2} - \text{RAO}_{\eta_4} - \frac{l}{hg} \text{RAO}_{\ddot{s}_3} \end{aligned} \quad (14)$$

### 3.8 Calculating Responses and Their Operators

To perform the operability calculations in `Matlab` with a high resolution in sea states, the step before the sea states, the RAOs, are exported from `Octopus Office 6`. For some derived criteria like MSI the RAOs are for the motions they are derived from, in the case of MSI, the vertical acceleration. Consequently the MSI index must be calculated in `Matlab`. For other criteria, like MII, it is necessary to calculate the desired operator, like rate of events. The response spectrum is



(b) Discrete heat map with the same data, and bin size as Fig 7a.

**Figure 7:** The total number of recorded sea states is 458 145. Both plots show the same data.

obtained by multiplying the square of the RAO with the sea spectrum from equation (8), then different calculations are performed depending on the operator.

After performing the calculations described below, the criteria based on local motion but where the relevant location is actually two symmetrically placed locations, have to be somewhat modified. Either the maximum or the sum, depending on the operator, of the two sides should be taken as the level to compare with the criteria in Tab 3. Thanks to the symmetry of both the ship and the sea spectra, the result of the opposite side of the ship is the same as the result from the negative heading angle.

### 3.8.1 Single Significant Amplitude (SSA)

Given the definition of the sea spectrum used in equation (7) the area under the spectrum curve equals the variance  $\sigma^2$ , and since  $SSA = 2\sigma$  we get

$$SSA(\eta) = 2 \cdot \sqrt{\sigma^2} = 2 \cdot \sqrt{\int_0^\infty S^\eta(\omega) d\omega}$$

### 3.8.2 Motion Induced Interruption

Since instantaneous values of wave elevation follow the normal distribution, the responses will also follow the normal distribution for linear combinations of RAOs. It is therefore assumed that also the Rayleigh distribution of the peak values remain in the responses. The probability of an MII is then calculated using the cumulative distribution function for the Rayleigh probability distribution to find the probability that a peak in acceleration ratio is higher than the tipping coefficient.

$$P[\text{MII}] = e^{-\frac{(l/h)^2}{R}}$$

$$R = \int_0^\infty S^{\text{MII}}(\omega) d\omega$$

To calculate the rate of MIIs, which criteria is formulated in terms of, the encounter period  $T_e$  is needed, according to Journée and Adegeest (2003) it is

$$T_e = 2\pi \sqrt{\frac{m_0}{m_2}} \quad (15)$$

where  $m_n$  is the  $n$ -th spectral moment, by Journée and Adegeest (2003) defined as

$$m_n = \int_0^\infty S^{\text{MII}}(\omega) \cdot (\omega_e)^n d\omega \quad (16)$$

Next the rate of MIIs in  $\text{MII}/\text{h}$  is

$$\dot{N}_{\text{MII}} = 3600 \cdot \frac{P[\text{MII}]}{T_e}$$

To be specific, what has been obtained is the number of times per hour a person might stumble to one of the directions port or starboard, depending on if the RAO from Equation (13) or (14) were used. In order to get the real rate of MIIs, the number of times the person might stumble regardless of direction, results from the two should be added at this final stage.

### 3.8.3 Point Submergence

The rate of point submergence is calculated from the RAOs for relative vertical motion, using the same probabilistic calculations as for MIIs, with the limit being the height of the point of interest from the still water surface so that

$$P[\text{submergence}] = e^{-\frac{(z-T)^2}{R}}$$

$$R = 2 \cdot \int_0^\infty S^{\eta_{3,\text{relative}}}(\omega) d\omega$$

where  $z$  is the vertical position of the point of interest. The rate of occurrence is also calculated in the same way as for MIIs, with  $T_e$  according to Equation (15) and spectral moments

$$m_n = \int_0^\infty S^{\eta_{3,\text{relative}}}(\omega) \cdot (\omega_e)^n d\omega \quad (17)$$

### 3.8.4 Slamming

A slamming event is assumed to happen if the relevant point emerges from the water and returns with sufficiently high relative velocity. Therefore the probability of a slamming event is that of emergence *and* sufficient downward velocity. Since the vertical motion and velocity have a strong negative correlation in sinusoidal waves, it is important to count with phase, that way they can be assumed to be uncorrelated so that

$$P[\text{slamming}] = e^{-\left(\frac{(T)^2}{R_a} + \frac{(0.09\sqrt{Lg})^2}{R_b}\right)}$$

$$R_a = 2 \cdot \int_0^\infty S^{\eta_{3,\text{relative}}}(\omega) d\omega$$

$$R_b = 2 \cdot \int_0^\infty S^{\dot{\eta}_{3,\text{relative}}}(\omega) d\omega$$

where  $L$  is the waterline length (Rosén, 2007). Also

$$S^{\dot{\eta}} = i\omega S^\eta$$

The rate of occurrence is calculated in the same way as for MIIs and point submergence, with  $T_e$  according to equation (15) and spectral moments according to equation (17)

### 3.8.5 Motion Sickness Incidence Index

The recommendations on limits for MSI index by NATO STANAG 4154 (1997) that are followed, assume the usage of the method by O'Hanlon and McCauley (1974) for sinusoidal waves

$$\text{MSI} = 100 \int_{-\infty}^{\log \bar{s}_3} (\sigma \sqrt{2\pi})^{-1} e^{-((x - \mu_{\text{MSI}})^2 / 2\sigma^2)} dx$$

$$\sigma = 0.40 \log \bar{s}_3$$

Most papers use a different function based on the error function, this function does not coincide with the original one but is easier to use and more computationally efficient. The common formulation does not however have the correct range of function, which should be  $\text{MSI} \in [0\% \ 100\%]$ . To fix this the error function term is multiplied by  $1/2$ .

$$\text{MSI} = 100 \left[ \frac{1}{2} \pm \frac{1}{2} \text{erf} \left( \frac{\pm \log_{10} \frac{|\bar{s}_3|}{g} \mp \mu_{\text{MSI}}}{0.4} \right) \right] \quad (18)$$

with the following symbols

- MSI : Motion Sickness Incidence index
- erf : error function
- $\bar{s}_3$  : mean local vertical acceleration in a half wave cycle
- $\mu_{\text{MSI}}$  : parameter corresponding to the  $\bar{s}_3$  value for 50 % MSI, approximately

$$\mu_{\text{MSI}} \approx -0.819 + 2.32 (\log_{10} \omega_e)^2$$

An improvement of this method using superposition, proposed by Riola et al. (2004), can be used to be able to evaluate the MSI index for a spectrum of vertical accelerations, caused by irregular waves. In this project however, Equation (18) is used with 0.798 times the RMS value of local vertical acceleration as  $\bar{s}_3$  and  $\omega_e$  from  $T_e$  as calculated in Equation (15). This method is suggested by Lloyd (1989)

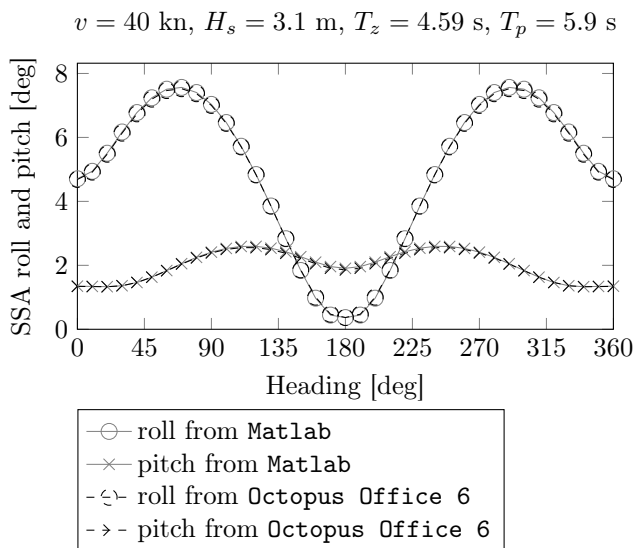


## 4 Validation

`Octopus Office 6` has previously been validated against model tests, something that will not be done again in this project, even if it could be relevant considering the size and speed of the analysed ship, a Froude number of 0.7 is above the limits of linear strip theory. The use of the strip theory is however not the point of this thesis, it is only used to calculate the RAOs which are input. Instead the validation done in this chapter is about the automation of response calculations done in `Matlab`, results and part results from the `Matlab` scripts are compared to results from `Octopus Office 6`. Note that not all of the validation was made with the final settings, and the values showed in the plots of this chapter are only for validation of the method and might therefore conflict with the results. Plots from intermediate steps without interesting details discussed in the text are placed in Appendix B.

### 4.1 Calculation of Responses

Starting with the simplest case, SSA roll and pitch angles in perfectly long crested seas and with no forward speed, there is a good fit between results from `Matlab` and `Octopus Office 6`, see Fig B.1. In `Octopus Office 6` long crested seas are represented by a spreading exponent in equation (8) of 9 999. Afterwards it is verified that the calculations of encounter spectra and such are correct by plotting the same motions but with forward speed. Figure B.2 shows this comparison with a good fit. Adding spreading to the wave spectrum to get a short crested sea state typical for wind waves smoothes the curves out, as can be seen in Fig 8 there is still an excellent fit.



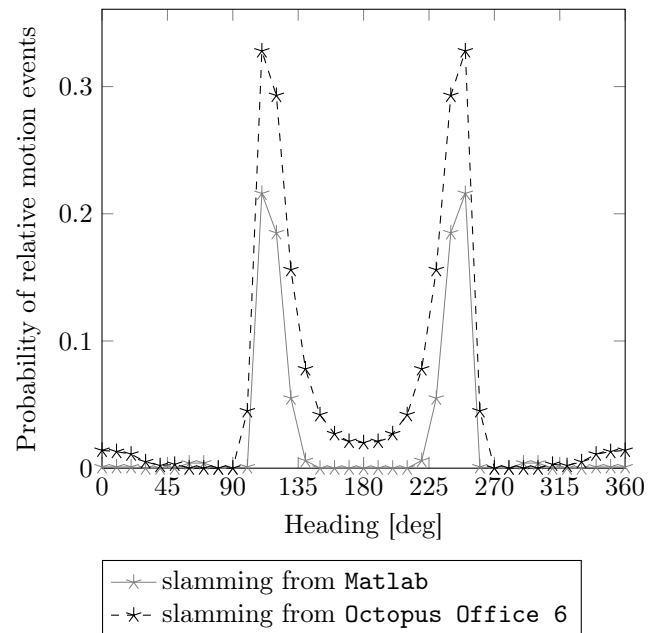
**Figure 8:** Comparison between SSA values of roll and pitch responses at 40 kn speed in short crested seas, from `Matlab` and `Octopus Office 6`.

### 4.2 Calculation of Operators

The other responses than roll and pitch have more complicated operators than SSA, for example rate of occurrence. These calculations, described in subsection 3.8, must of course also be verified. It is however first wise to check that the SSA of the underlying responses are correct. For MSI index that is local vertical acceleration, they are shown in Fig B.3. For the submergence and slamming criteria, that is the relative vertical motion between ship and water surface, at the exhaust pipes and the slamming point in the bow respectively, they are shown in Fig B.4. For MIIs it is the left hand sides of equations (11) and (12), one of them is shown in Fig B.5 and the other one is mirrored.

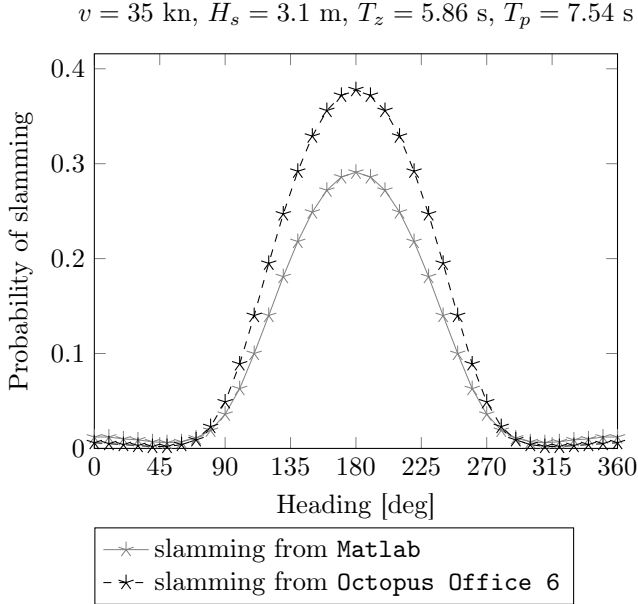
For submergence, slamming, and MIIs, where the desired metric is the rate of occurrence, there is one more intermediate step that can be validated. It is the probability of occurrence at a given wave. Figure 9 shows this for bow slamming, and Fig B.6 shows it for exhaust submergence and MIIs. For slamming we see the first example of a bad fit between `Matlab` and `Octopus Office 6`, this is because the latter uses both the relative velocity criterion developed by Ochi (1964) and the peak impact pressure criterion by Conolly (1974) according to Journée and Adegeest (2003). The `Matlab` script on the other hand, only uses the relative velocity criterion. Since neither can be considered to be very precise for the considered type of ship (Journée & Adegeest, 2003), this difference will be accepted. The probabilities of submergence and MIIs show an excellent fit.

$$v = 40 \text{ kn}, H_s = 3.1 \text{ m}, T_z = 4.59 \text{ s}, T_p = 5.9 \text{ s}$$



**Figure 9:** Comparison between probabilities of relative vertical motion events at 40 kn speed in perfectly long crested seas, from `Matlab` and `Octopus Office`.

When spreading is added again, the difference in slamming reduces, as is shown by Fig 10. Submergence is omitted here since it is calculated the exact same way as MIIs, shown in Fig B.7 with excellent fit.



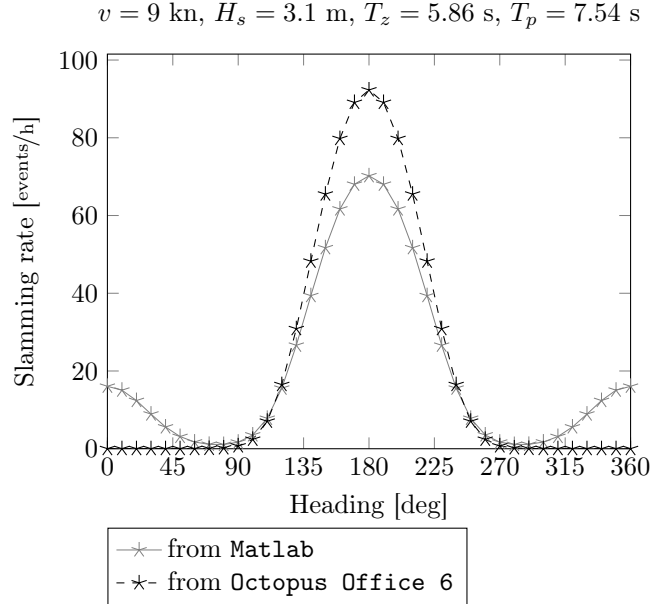
**Figure 10:** Comparison between probability of slamming events at 40 kn speed in short crested seas, from Matlab and Octopus Office 6.

Verification of the last step with long crested seas, that from probability to rate of occurrence of slamming now has to be done by using probabilities exported from Octopus Office 6, instead of calculated from the RAOs. The encounter period still has to be calculated from the RAOs. The resulting slamming rate shows a perfect match to the one exported from Octopus Office 6, as can be seen in Fig B.8. The rate of MII events plotted in Fig B.9 is as before a comparison between data calculated all the way from RAOs and exported results.

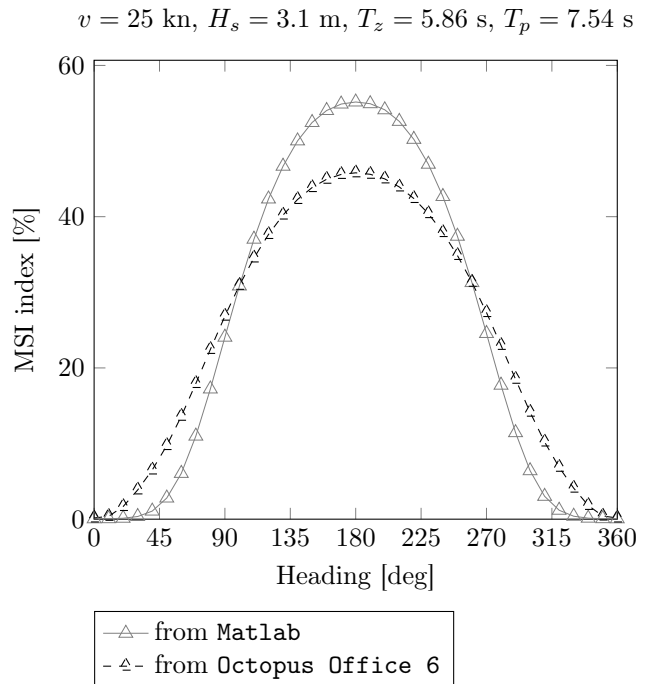
The MSI index has a decent fit, see Fig B.10, the difference most likely comes from how irregular seas are handled. When describing how *Seaway*, the predecessor of Octopus Office 6 does it, Journée and Adegeest (2003) cites the method by O’Hanlon and McCauley (1974) that is based on sinusoidal waves. subsection 3.8 describes how the Matlab script handles it.

The final responses in a short crested sea state does have some differences that were not present with the long crested seas, the encounter period is critical for calculating both rate of occurrence and MSI index. Calculating it is quite straight forward for long crested seas, and the way it’s calculated by Journée and Adegeest (2003) is in equations (15) and (16) in subsection 3.8, but with spectral moments for each relevant response spectrum. How Octopus Office 6 cal-

culates it in short crested seas is however unclear, using the same code that gives a perfect fit in long crested seas does not give a perfect fit in short crested seas. The Matlab script uses equation (16) where the input spectra has in an earlier stage been integrated over the spreading angle, the results can be seen in Figs 11 to 13

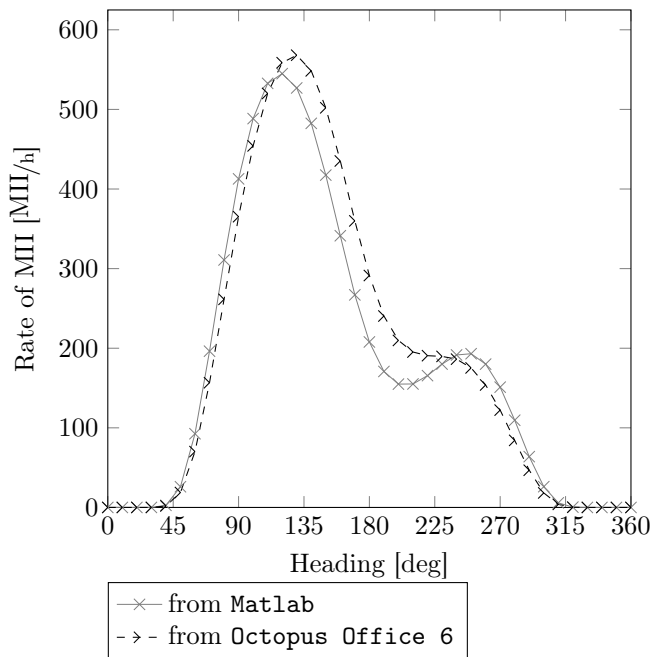


**Figure 11:** Comparison between slamming rates at 40 kn speed in short crested seas, from Matlab and Octopus Office 6.



**Figure 12:** Comparison between MSI index in the CIC at 40 kn speed in short crested seas, from Matlab and Octopus Office 6.

$v = 35$  kn,  $H_s = 3.1$  m,  $T_z = 5.86$  s,  $T_p = 7.54$  s In conclusion there are some differences between the



Matlab and Octopus Office 6 calculations when it comes to rate of events and MSI index despite extensive efforts to find the cause, and a lot of testing. This is of course unfortunate, however, the responses are still reasonable, and the error might just come from different but equally valid methods. The worst fitting criterion is slamming, that has an error also in the pure probabilities, the error in slamming also varies more with speed and sea state than the others.

**Figure 13:** Comparison between rate of MII on the ammunition deck at 40 kn speed in short crested seas, from different sources.



## 5 Results

From the calculations performed the main result is the Percent Time Operable (PTO), a general measure on sea keeping performance. However in the PTO the information on what sea states, criteria, headings, and speed causes the disruptions in operability is lost. This information is instead portrayed here in plots and tables of the data that is aggregated into the PTO and some particularly interesting situations and scenarios.

### 5.1 Percent Time Operable

Operability can be defined in different ways and which one is suitable depends on the task of the ship. Since the Visby class corvettes have many diverse missions, with very different requirements on speed and tolerances on heading, different methods have to be used. The one thing that all missions have in common, is that at a given sea state, will the ship never be considered operable unless the criteria are fulfilled for at least one direction at zero speed.

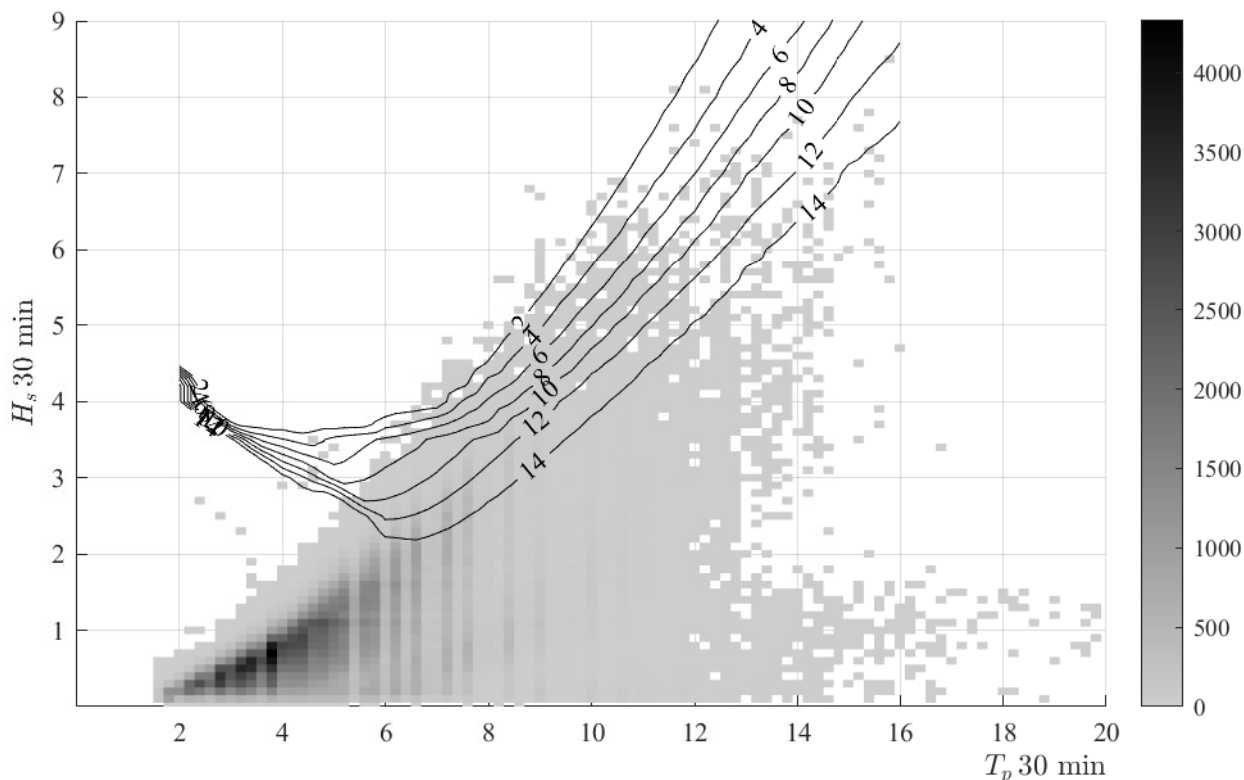
In general the method of calculating PTO in this project is as follows, the operability is averaged over all headings, if there was a known probability distribution of desired headings this would be a weighted average, but this is not the case, see the project limitations. The mean is then multiplied by the probability

of the sea state in question and then summed for all sea states to get the PTO

For Transit and Patrol (TAP) the mission speed profile will be assumed to be 15 kn at all times, see Appendix A, but operability will not be binary, if it is possible to travel at 12 kn the operability for that situation is considered to be 0.8. Furthermore if a course change of  $10^\circ$  makes it possible to travel at 15 kn the velocity made good is  $15 \cdot \cos 10^\circ \approx 14.8$  kn and the operability will be considered to be  $14.8/15 \approx 0.98$ . This approach should better match the requirements for TAP than considering the ship inoperable for that heading.

The main principle of the calculation is visualised in Fig 14 where the probability of each sea state is combined with the heading averaged velocity made good. PTO is proportional to the double integral of the product of the two overlaid plots.

When it comes to SUW, ASW, MCM, and SAR a speed reduction or course deviation might not be viable and a more traditional approach is used, where the ship is considered operable if and only if it can travel at the desired speed, assumed to be 35 kn except for MCM, where 3 kn is used. This approach is suggested by for example Rosén (2007) who references therein to Lloyd (1989). The roll and pitch limits for launching torpedoes during ASW is only considered at a stand still,



**Figure 14:** Maximum velocity made good averaged over desired headings, in kn, during the TAP mission, overlaid on the statistical distribution of sea states from Fig 7b.

it is not assumed to be necessary to be able to launch torpedoes while moving.

For the last two missions, NAO and WRL, speed and heading are assumed to be less relevant, and the ship is considered operable in the sea state if there is any heading in which the criteria are fulfilled at zero speed. The PTO for each above missions, by the criteria in Tab 3, are presented in Tab 6 below by season. The last column represents the full year, but is calculated as a mean of the four seasons instead of simply from all recordings to prevent bias towards the seasons that have a higher percentage of the recordings, see subsection 3.5.

**Table 6:** Percent Time Operable.

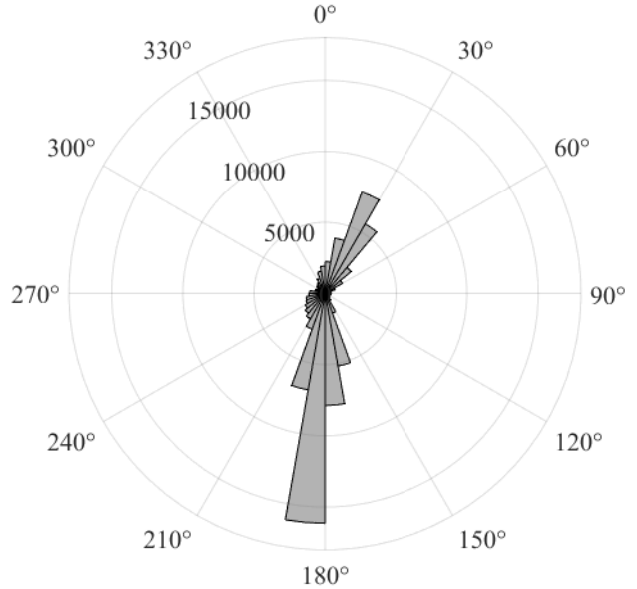
Task	Winter	Spring	Summer	Fall	Mean
TAP	97.3	99.6	99.8	98.6	98.8
SUW	84.9	94.9	96.4	89.4	91.4
ASW	87.7	95.8	97.2	91.8	93.1
MCM	91.0	97.2	98.1	94.0	95.1
SAR	90.1	96.8	97.9	93.4	94.6
NAO	95.8	99.2	99.6	97.9	98.1
WRL	95.6	99.0	99.5	97.5	97.9

The values are largely as expected, winter is consistently the worst season, and summer the best. Autumn is also consistently worse than spring and summer. It is also evident that allowing course deviations make a large difference on PTO with TAP, NAO, and WRL scoring consistently higher than the other missions, even MCM where the speed is 3 kn, indicating that allowing course deviations make a larger difference than allowing a reduction of speed.

One more mission will be considered on its own, it is based on a scenario of escorting supply ships to Gotland. The scenario is made up but plausible, and consists of sailing from behind Öland, for example the port of Oskarshamn, to the port of Visby, namesake of the Visby class corvettes, and back. This route passes closely by the Knolls Grund boj, providing the sea state data, and the course from northern Öland to Visby is 073°, making the course for the return trip 253°. It is assumed that the desired course and a speed of 25 kn must be maintained for the ship to be considered operable, and the criteria for TAP are used.

Now that the course is well defined, it is possible to also take the relative course between ship and dominant waves. Despite the prevailing winds in this part of the world being westerly, the surrounding land makes the dominant wave direction from south to north, see Fig 15. This way the seas have a much greater fetch distance, all the way from Poland, coming in parallel to the eastern shores of Öland. There is also a significant portion of sea states coming from north-

north-east, with a fetch from Finland, along the north-western shores of Gotland.



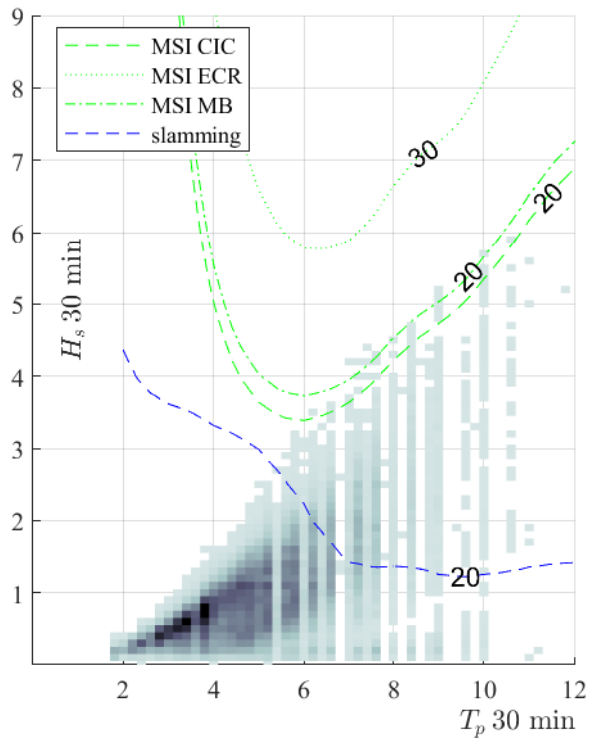
**Figure 15:** Histogram of sea states' main wave directions at Knolls Grund boj.

There is however a correlation between wave direction, height, and period which is accounted for in the PTO calculations. Table 7 presents the resulting PTO numbers for this scenario

**Table 7:** PTO for an escort mission between Oskarshamn and Visby.

Course	073°	253°
Winter	80.8	82.9
Spring	95.2	95.2
Summer	98.6	98.5
Fall	89.9	90.4
Mean	91.1	91.8

To finally get a hint on what criteria are limiting, the limits are plotted for the most common main relative wave direction on the eastbound voyage, 290° relative to the ship, at 25 kn speed. Figure 16 show that for all wave periods, slamming is the limiting criterion with regards to allowed wave height.

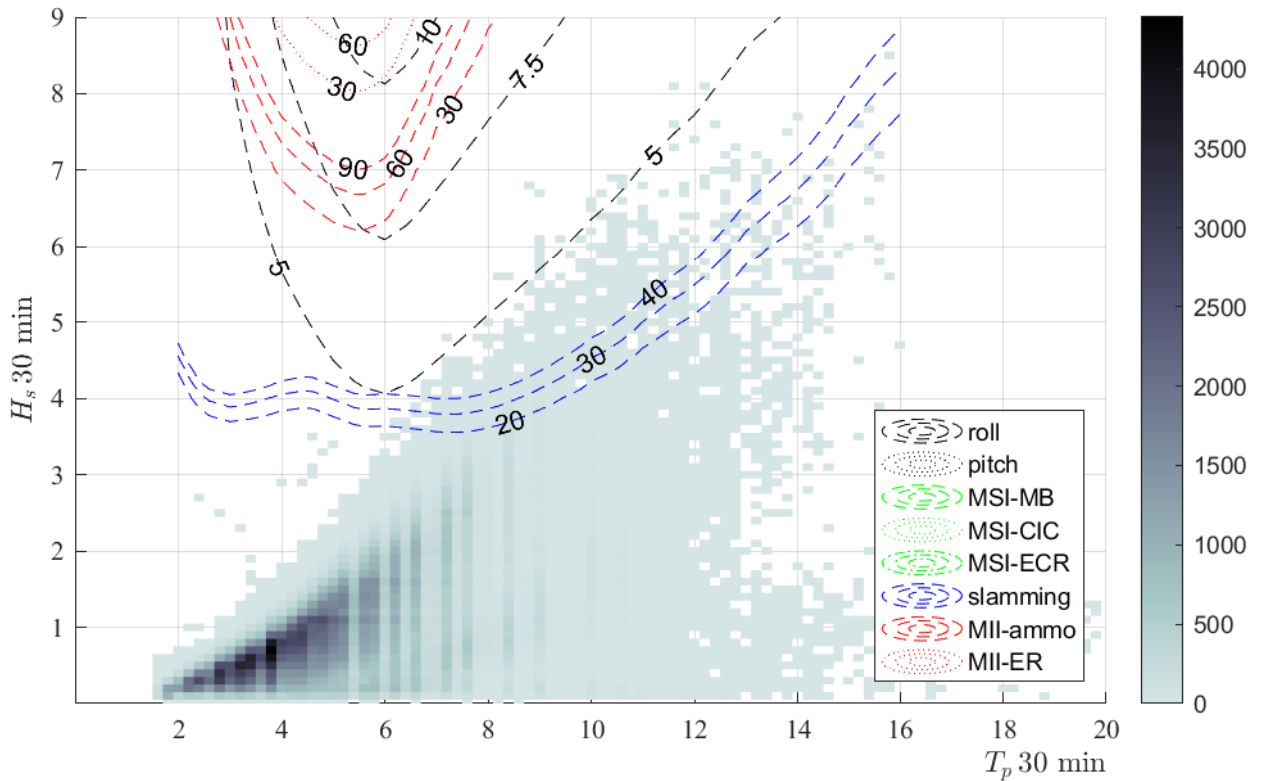


**Figure 16:** Response level limits in most common main relative wave direction on the route to Gotland. MSI in percent and slamming in number per hour.

## 5.2 Sensitivity to Criteria Levels

To get an understanding of what criteria are limiting, it is useful to plot the different criteria levels at a given combination of heading and speed. In Figs 17 to 21 this is done with isolines at the criteria levels from Tab 3 as well as other potential criteria levels to hint on the sensitivity to criteria levels.

At 35 kn speed the limiting factor in terms of how high waves can be operated in, is either slamming, MIIs on the ammunition deck, or MSI, depending on the course. For those missions where full speed is assumed these are the criteria that affect the PTO the most. The allowed wave height changes a lot more with a change in roll limit however, which is why roll would suddenly be limiting in beam and following quartering seas if the roll limit was reduced to 5° SSA, at least in longer waves. Consequently the level of all these criteria have the potential to affect the PTO.



**Figure 17:** Response levels while going 35kn in following seas.

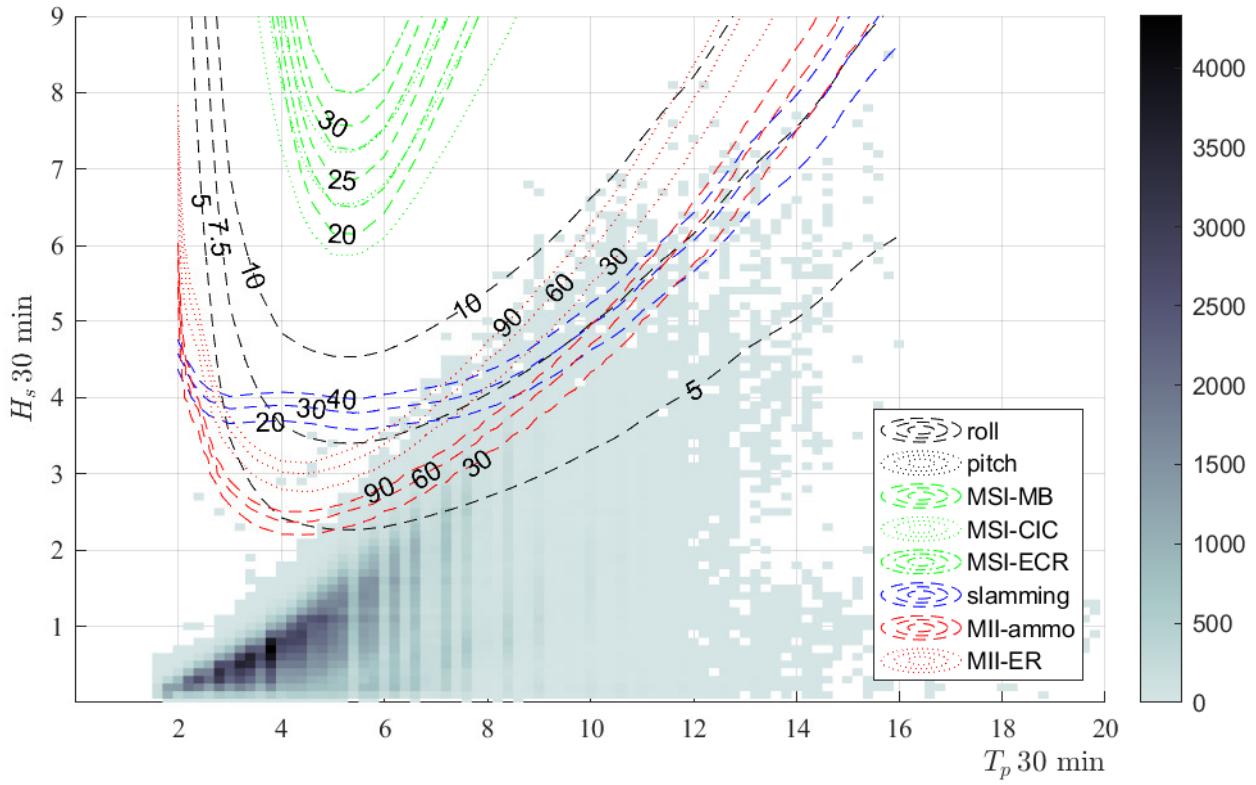


Figure 18: Response levels while going 35kn in following quartering seas.

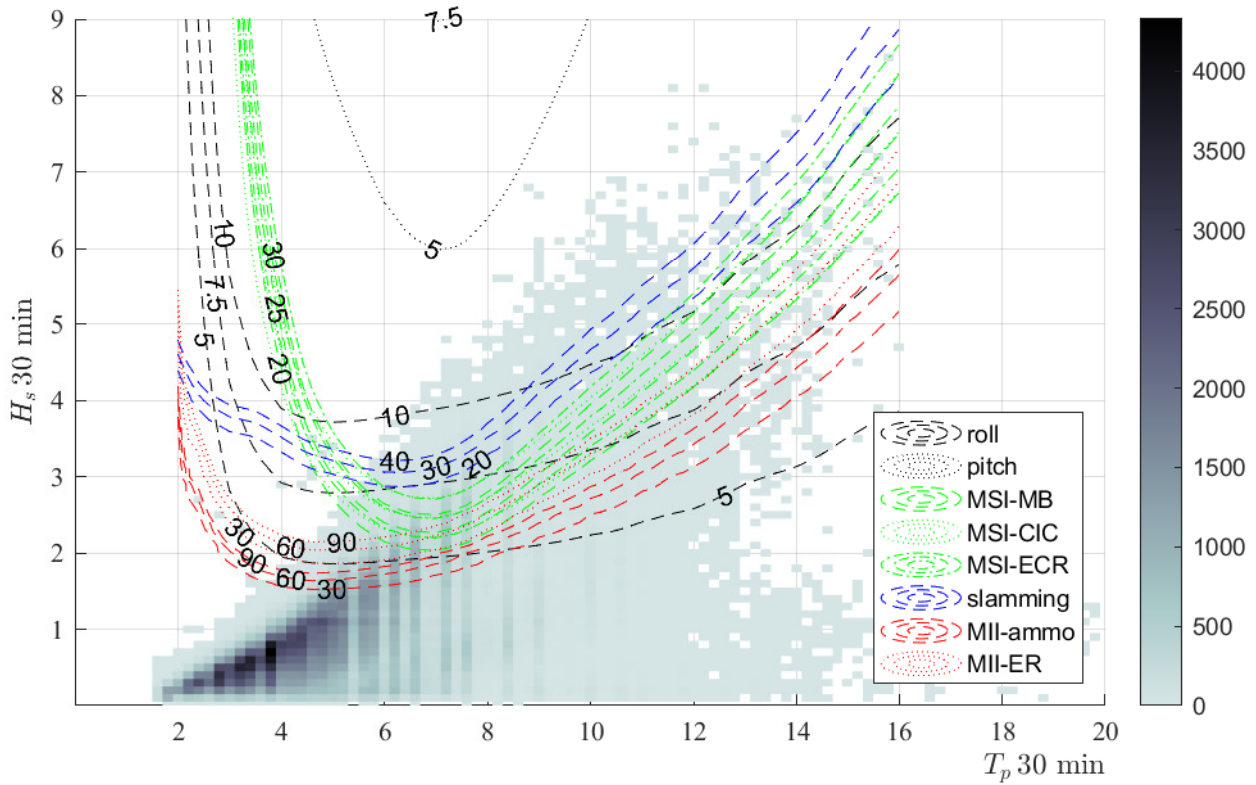


Figure 19: Response levels while going 35kn in beam seas.

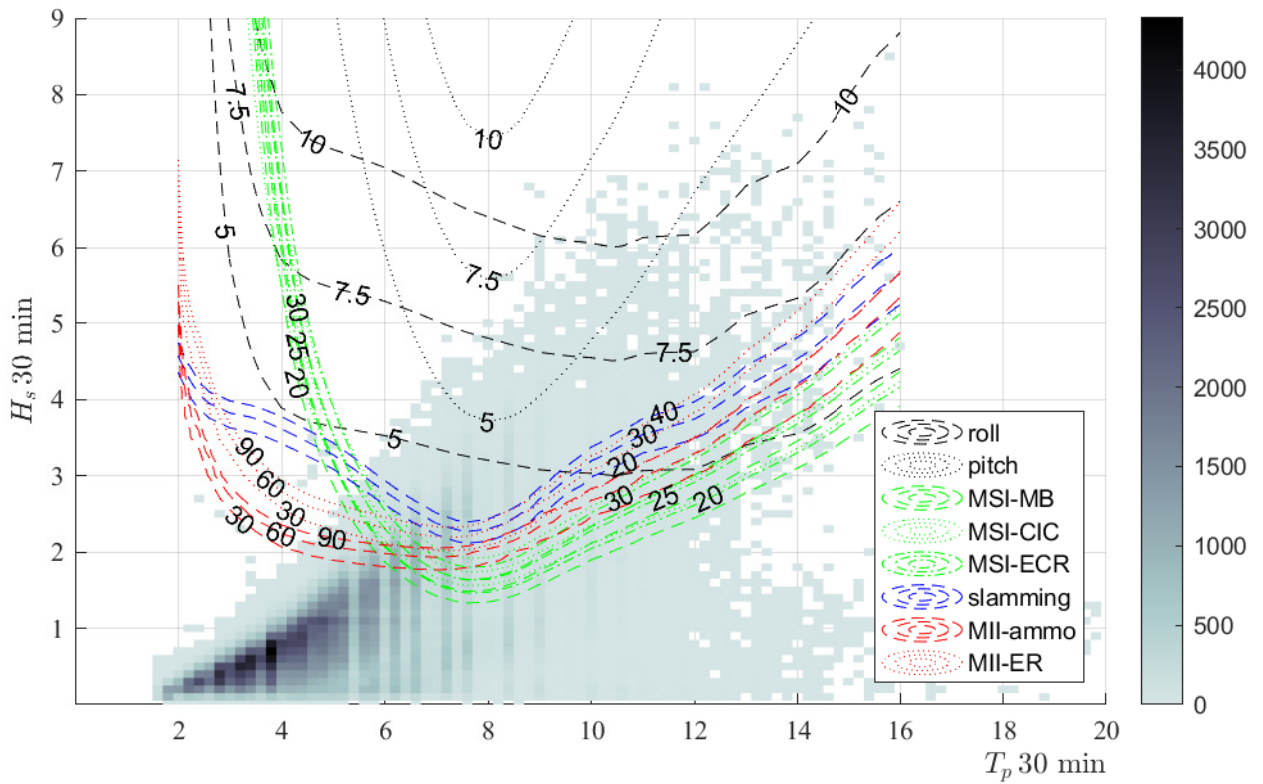


Figure 20: Response levels while going 35kn in head quartering seas.

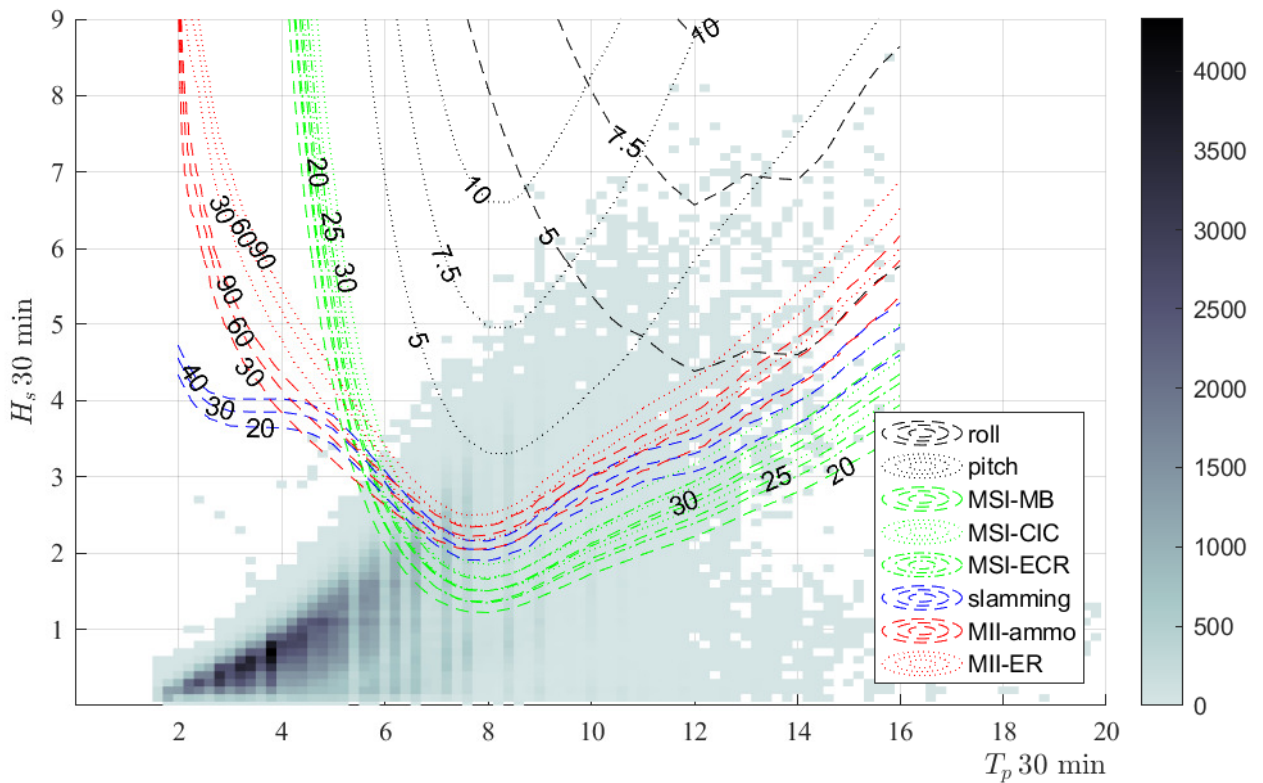


Figure 21: Response levels while going 35kn in head seas.

Using a modified set of criteria with limits at 5° SSA on roll and pitch, 20 % MSI everywhere, 20 slamming events per hour, and 30 MIIs per hour the lower PTO values in Tab 8 are obtained. Similarly, when using 10° SSA roll and pitch, 30 % MSI, 40 slamming events, 5 submergence events, and 90 MIIs per hour the higher PTO values in Tab 9 are obtained.

**Table 8:** PTO with pessimistic criteria.

Task	Winter	Spring	Summer	Fall	Mean
TAP	97.3	99.6	99.8	98.6	98.8
SUW	77.1	91.2	93.7	83.5	86.4
ASW	79.6	92.1	94.4	85.7	88.0
MCM	88.8	96.3	97.5	92.3	93.7
SAR	86.5	95.1	96.6	90.6	92.2
NAO	95.6	99.2	99.5	97.7	98.0
WRL	94.3	98.6	99.1	96.7	97.2

**Table 9:** PTO with optimistic criteria.

Task	Winter	Spring	Summer	Fall	Mean
TAP	99.2	99.9	100.0	99.6	99.7
SUW	88.1	96.1	97.3	91.8	93.3
ASW	90.6	96.9	98.0	93.9	94.9
MCM	92.6	97.8	98.5	95.2	96.0
SAR	91.5	97.2	98.1	94.4	95.3
NAO	98.0	99.8	99.9	99.2	99.2
WRL	97.1	99.4	99.7	98.4	98.7

Finally the effect of reducing the limit on slamming is evaluated, not just because the limit was set somewhat arbitrarily as discussed in subsection 3.2, but also because the validation showed that the calculation of slamming is flawed. Table 10 shows what the PTO would be if the stricter limit of 20 slamming events per hour was used for all criteria, the difference is insignificant.

**Table 10:** PTO with stricter slamming limit.

Task	Winter	Spring	Summer	Fall	Mean
TAP	97.3	99.6	99.8	98.6	98.8
SUW	84.9	94.9	96.4	89.4	91.4
ASW	87.7	95.8	97.2	91.8	93.1
MCM	90.8	97.1	98.1	93.9	95.0
SAR	90.0	96.8	97.9	93.4	94.5
NAO	95.6	99.2	99.6	97.8	98.0
WRL	95.5	99.0	99.5	97.5	97.9

## 6 Discussion

Eight different criteria came out of studying theory and practical knowledge of the ships, these focus heavily on the well-being and performance of the crew, but also represent limits for the ship and the ability to use the weapons. Despite the amount of research that has gone into developing seakeeping criteria it seems more is needed to have a formula of the connection between magnitude of accelerations and reduction of cognitive performance (Guézou et al., 2022).

### 6.1 Conclusions

While the many limitations of this project make the use of the resulting PTO limited, there are some points to be made about the method but also about the results. Recalling the scope of the project, one important part was to investigate the circumstances when the criteria are not fulfilled, since PTO is not the ultimate measure on sea keeping performance in contrast to a merchant ship, with the percentage of time it can earn money. Here the ultimate measure is rather if the ship fails or succeeds with its mission, potentially kill or get killed. Therefore it is reasonable to measure how often the potential enemy can operate while the friendly ship cannot, especially during seasons that are otherwise favourable for starting an attack. This includes plenty of unknowns, but one important point can be made.

Both Fig 14 and Figs 17 to 19 show that particularly the shorter wave sea states are troublesome. This is somewhat expected from small ships like the Visby class corvettes but not from bigger ships that a potential enemy might use. That is an important takeaway. In a way these plots show that it could be more reasonable to talk about limits on wave slope than wave height, since wave slope:

$$\frac{H}{\lambda} = \frac{2\pi}{g} \cdot \frac{H}{T^2} \quad (19)$$

curves of equal wave slope would have the shape of  $H$  being proportional to  $T^2$ . However when heading into the seas the shortest waves are not the most problematic, as can be seen in Figs 20 and 21

The results show that PTO is generally over 90 %, for some missions closer to 100 %. The main factor causing the difference between different missions also seem to be whether or not course deviations can be tolerated, rather than speed reduction. This reaffirms that whenever it is possible, implying that the officer on watch will likely do it, course deviations will improve operability, and should therefore be considered in these theoretical calculations.

When it comes to what criteria are limiting, the results indicate that most of the criteria will either be limiting

or close to limiting at some point. This can be taken as a sign of a good design without any obvious weakness, as if there was a single criterion that was constantly limiting.

### 6.2 Recommendations for Future Work

As there are many limitations listed in section 1 Some research could be done to improve the seakeeping criteria used and some could be done to better relate PTO to the risk presented to national security. examples

#### 6.2.1 Using Accelerometer Data and Whole-body Vibrations Criteria

The wave buoys that recorded the sea states used in this project save more than the one data point per hour that is readily available on SMHI's website, the instantaneous elevations are also saved, which allows for determining all five variables in the JONSWAP spectrum, for the particular location.

Because of its CFRP construction the Visby class corvettes are very stiff, something that can be felt as an increase in shock and whole-body vibrations compared to similar sized steel ships (Backman, 2023). These motions are bad for both health and comfort (SS-ISO 2631-1, 1998). The strip theory method used in this project is unsuitable for evaluating shocks, which calls for future projects to look into these issues. Fortunately HSwMS Visby had accelerometers installed in some seats (Öhrstedt, 2023), the data from these accelerometers could possibly be compared to data from a series of papers by (de Alwis & Garne, 2021) where accelerometer data from the seats of a smaller high performance boat was correlated to pain experienced by the crew.

In classified format there were also such comparisons made in rough seas during the sea trials of HSwMS Visby (Alba, 2023), these and likely other classified data could probably serve as a basis of more accurate seakeeping criteria for a classified operability analysis.

#### 6.2.2 Criteria for Launching the VDS

During its launch the VDS is a hanging load, with the potential to hit the water jet propulsors. It should be possible to make criteria for avoiding this, which would be relevant for example for the ASW mission.

#### 6.2.3 Other detailed scenarios

There might be other relevant scenarios like the escort mission to Gotland that could be studied in more detail. One example could be a similar escort mission but on Sweden's vital trade routes between the west coast ports and beyond Skagen. In a classified format naval doctrine might give information on courses also for other missions like SUW and ASW.

If the other more general mission sets in this report would be evaluated by location, not just by season, it might also be possible to set a probability distribution on headings, simply from patrolling likely being parallel to a coast line while SAR could be more likely to go straight out from the coast line.

#### **6.2.4 Operability of Potential Adversaries' Ships**

As previously established, knowledge about the opposing fleets operability limitations is key to setting requirements on own operability. Therefore a study similar to this one but on naval ships from a potentially hostile country in the region could be a good idea.

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## Appendices

Appendix	Document name	Page
A	The Visby Class Corvette	32
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## A The Visby Class Corvette

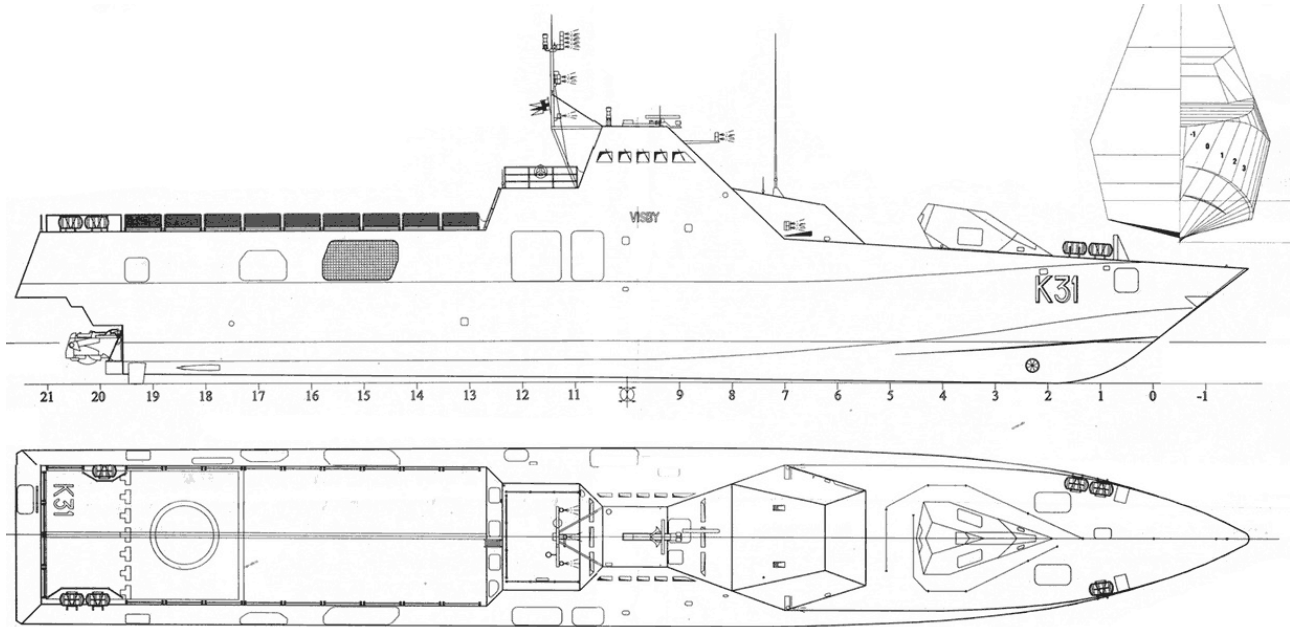


Figure A.1: Open source blueprint of HSvMS Visby (Adopted from Blueprints, n.d.).

### Description

Light weight stealth corvette.

The following numbers are estimated for the design water line from sometimes conflicting sources with different precision on digits. Figure A.1 has also been used as a complement with best estimates of vertical and horizontal scaling from the measurements in the ThyssenKrupp Marine Systems Kockums (2012) trim and stability booklet. Sources: (SAAB, 2020), (Swedish Defence Materiel Administration, 2022), (Swedish Armed Forces, 2021), (ThyssenKrupp Marine Systems Kockums, 2012), (Backman, 2023)

#### Main Particulars

Length overall ( $L_{OA}$ )	72.77	[m]
Length waterline ( $L_{WL}$ )	61.50	[m]
Beam overall ( $B_{OA}$ )	10.40	[m]
Beam waterline ( $B_{WL}$ )	9.12	[m]
Draft ( $T$ )	2.4	[m]
Height from keel line	21.4	[m]
Vol. displacement ( $\nabla$ )	636	[m <sup>3</sup> ]

#### Machinery

Gas turbines	16	[MW]
Diesel engines	2.6	[MW]

#### Operational

Max speed ( $v_{max}$ )	>35	[kn]
Transit speed ( $v_t$ )	15	[kn]
Crew	43	[persons]
Range at $v_t$	2 500	[NM]

#### Non-dimensional Coefficients Under-water Body

Froude number ( $Fn$ )	0.73	$v_{max}/\sqrt{L_{WL}g}$
Froude number volumetric ( $Fn_{\nabla}$ )	1.96	$v_{max}/\sqrt[3]{\nabla g}$
Mainframe aspect ratio	3.8	$B_{WL}/T$
Waterplane aspect ratio	6.7	$L_{WL}/B_{WL}$
Slenderness	7.2	$L_{WL}/\sqrt[3]{\nabla}$
Long. center of buoyancy ( $LCB$ )	7.4	[% aft of mid]
Long. center of flotation ( $LCF$ )	6.9	[% aft of mid]
Block coefficient ( $C_B$ )	0.47	$\nabla/L_{WL}\cdot B_{WL}\cdot T$
Vertical prismatic coefficient ( $C_{VP}$ )	0.56	$\nabla/T\cdot A_{WP}$
Waterplane area coefficient ( $C_{WP}$ )	0.83	$A_{WP}/L_{WL}\cdot B_{WL}$

#### Equipment for Maneuvering & Seakeeping

Propulsion	2	Kamewa 125 water-jets
Bow thruster	1	[pc]
Stabilizing fins	2	[pc]
Keel		on center line
Ballast Water Tanks	12.3	[m <sup>3</sup> ]

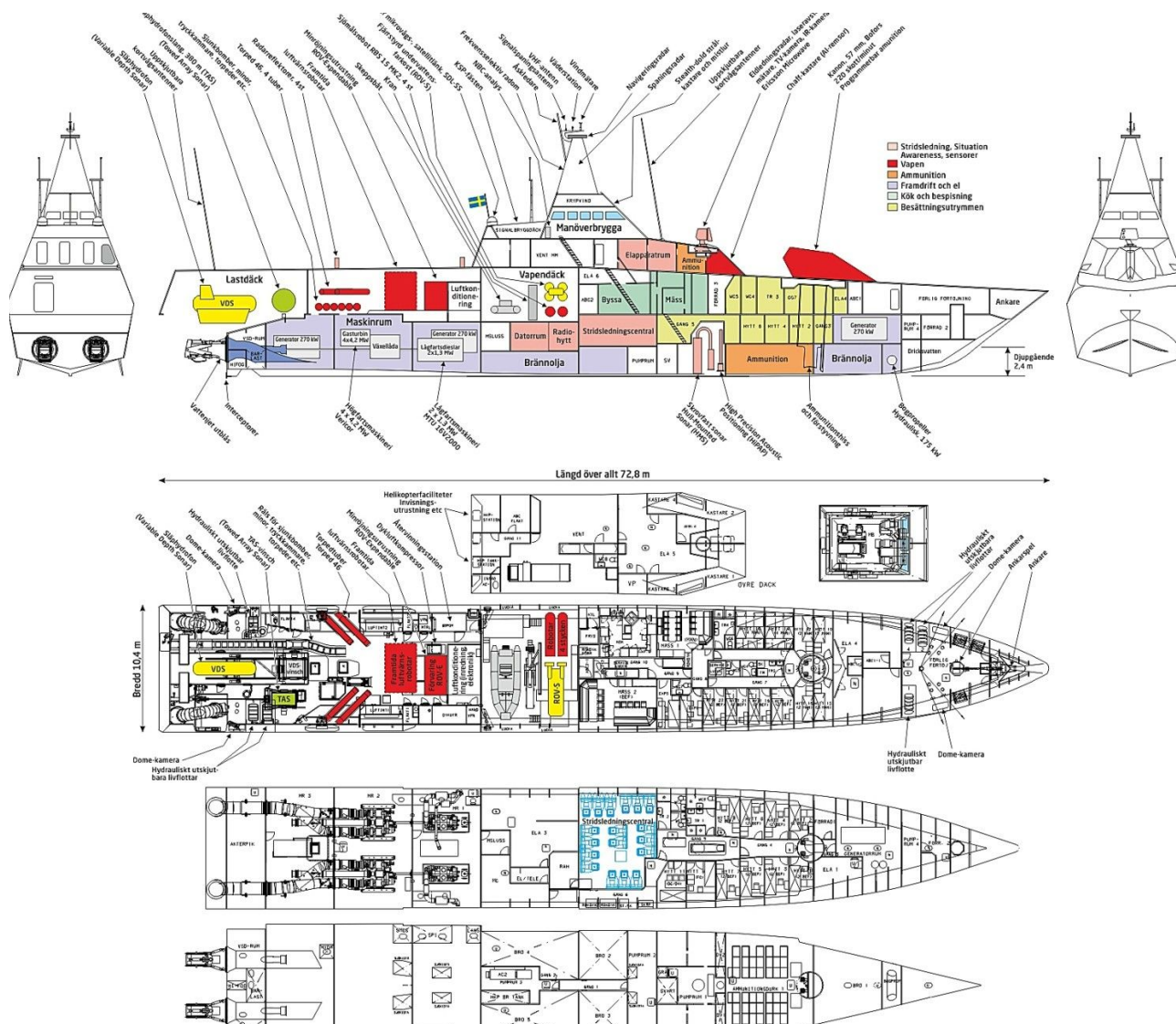


Figure A.2: General arrangement plan of the Visby class corvette (adopted from Städje, 2014a).

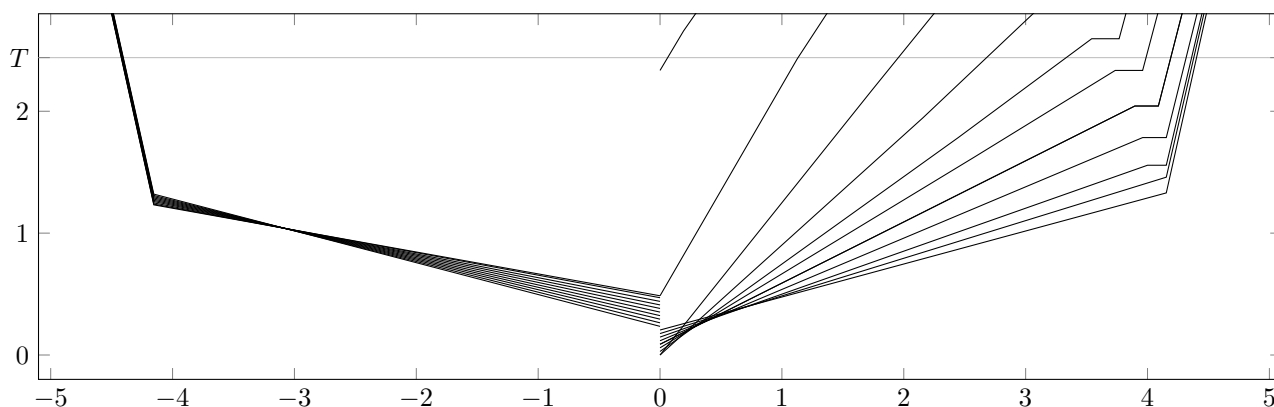
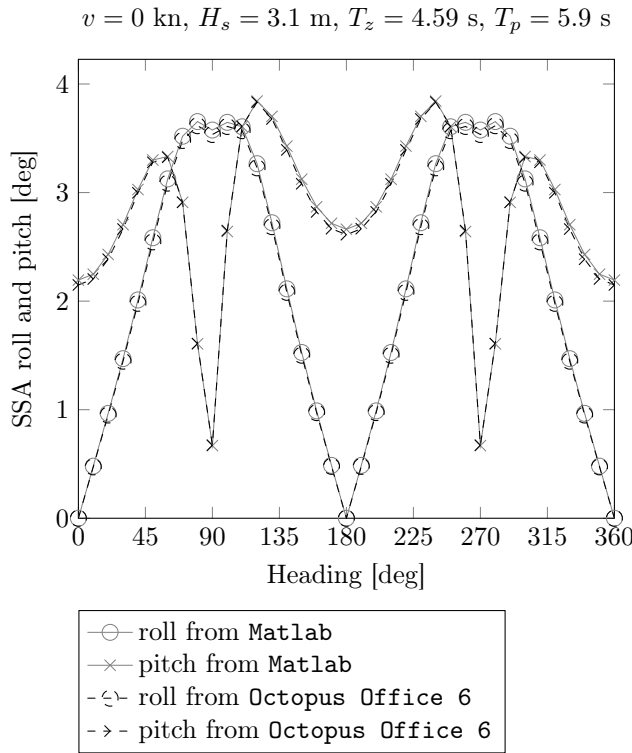


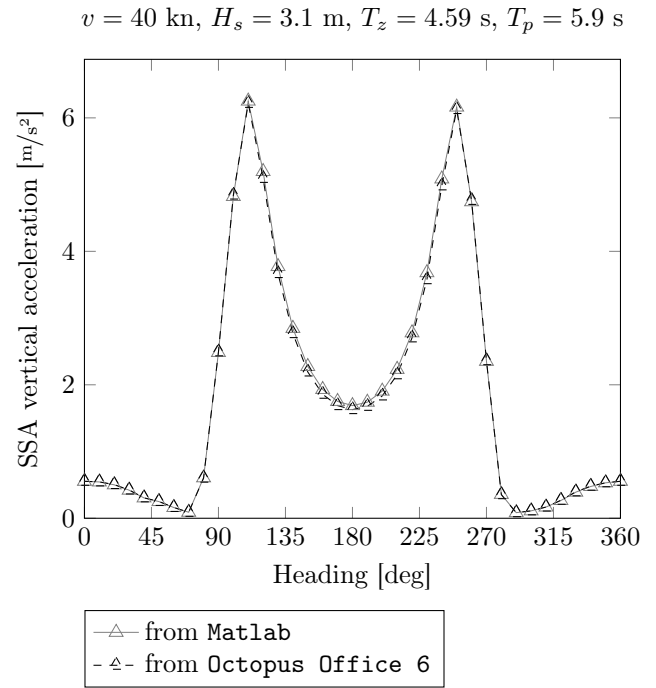
Figure A.3: An estimate of the hull lines of the under water body.



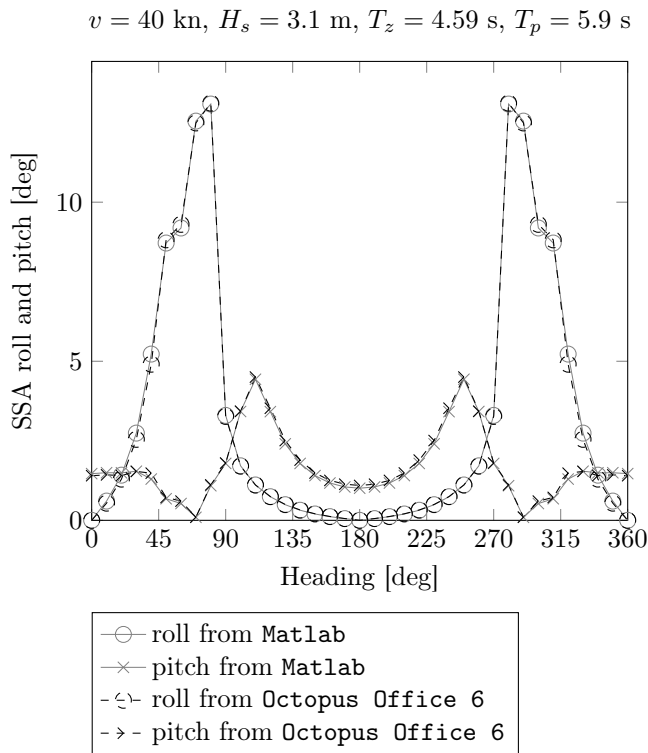
### B Plots for Additional Validation Steps



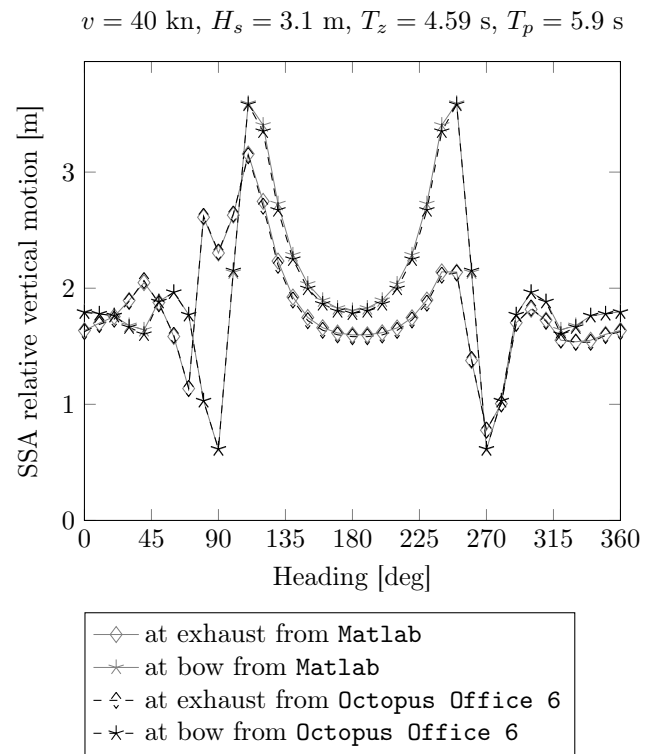
**Figure B.1:** Comparison between SSA values of roll and pitch responses at zero speed in perfectly long crested seas, from Matlab and Octopus Office 6.



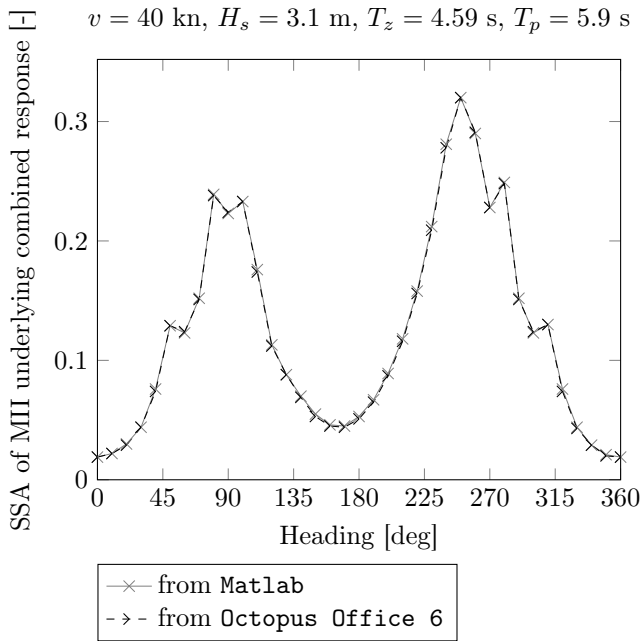
**Figure B.3:** Comparison between SSA values of vertical acceleration at the bridge at 40 kn speed in perfectly long crested seas, from Matlab and Octopus Office 6.



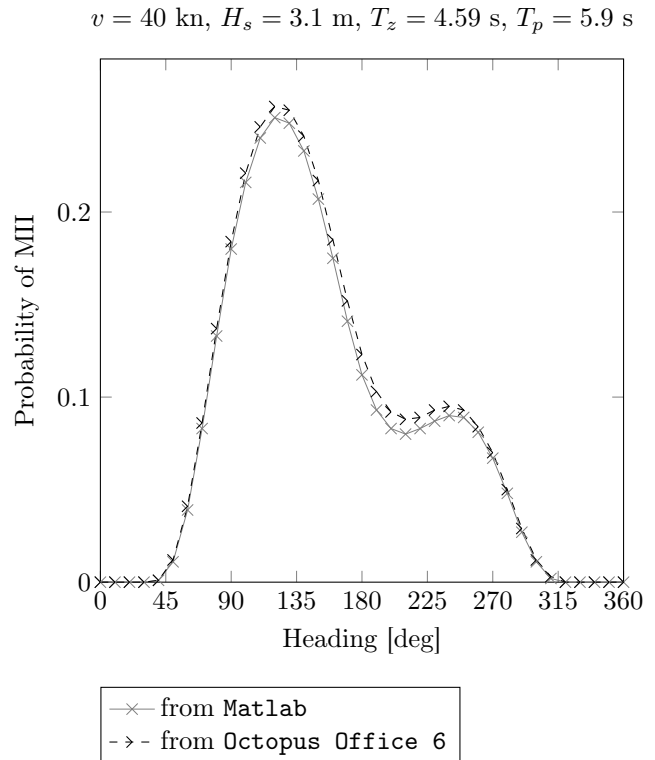
**Figure B.2:** Comparison between SSA values of roll and pitch responses at 40 kn speed in perfectly long crested seas, from Matlab and Octopus Office 6.



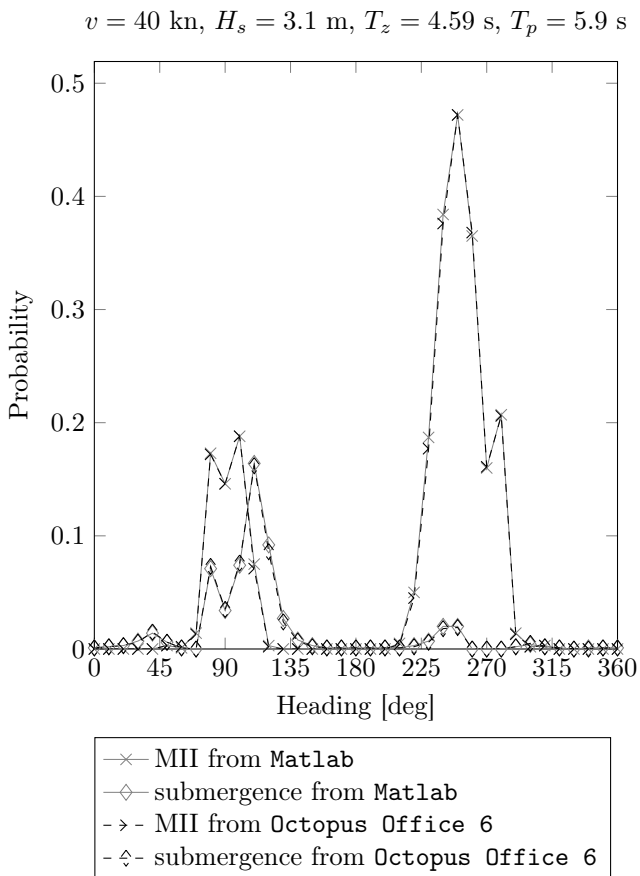
**Figure B.4:** Comparison between SSA values of relative vertical motion at the relevant locations at 40 kn speed in perfectly long crested seas, from Matlab and Octopus Office 6.



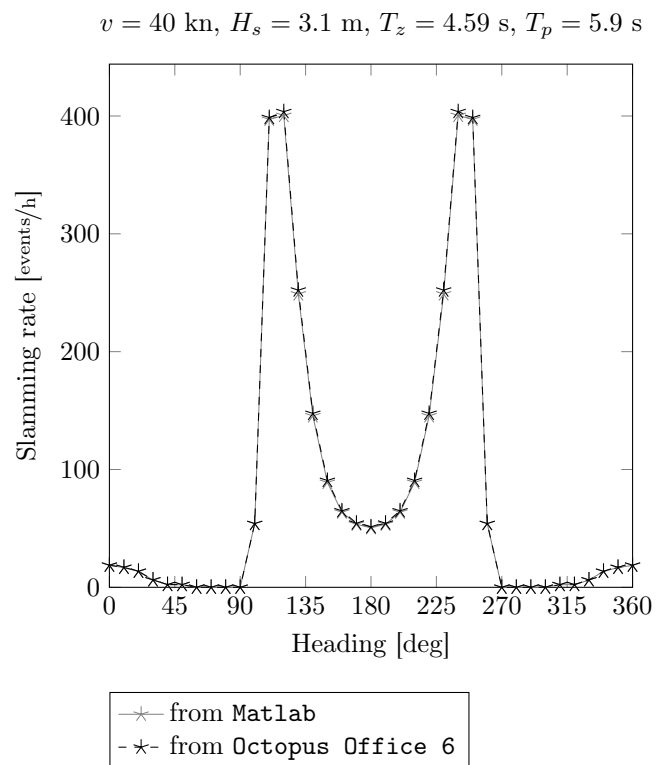
**Figure B.5:** Comparison between SSA values of MII underlying combined response at the ammunition deck at 40 kn speed in perfectly long crested seas, from Matlab and Octopus Office 6.



**Figure B.7:** Comparison between probability of MII on the ammunition deck at 40 kn speed in short crested seas, from Matlab and Octopus Office 6.

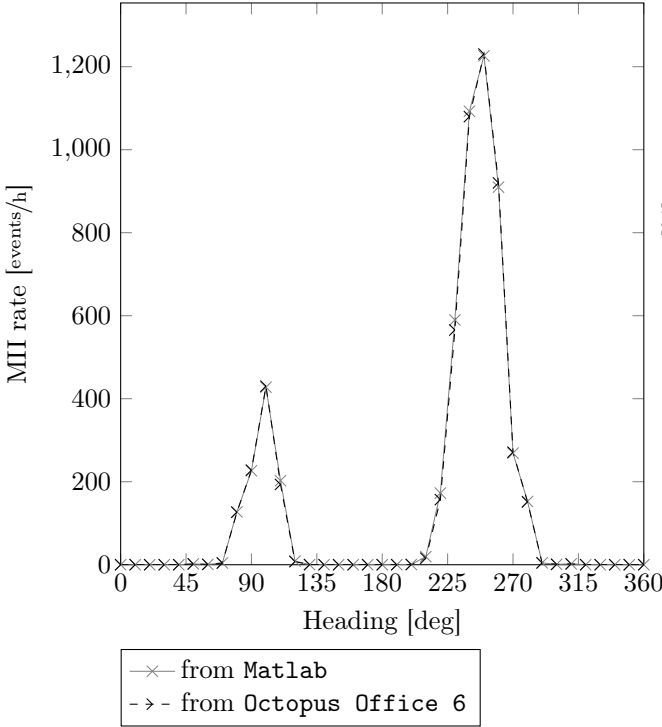


**Figure B.6:** Comparison between probabilities of events at 40 kn speed in perfectly long crested seas, from Matlab and Octopus Office 6.



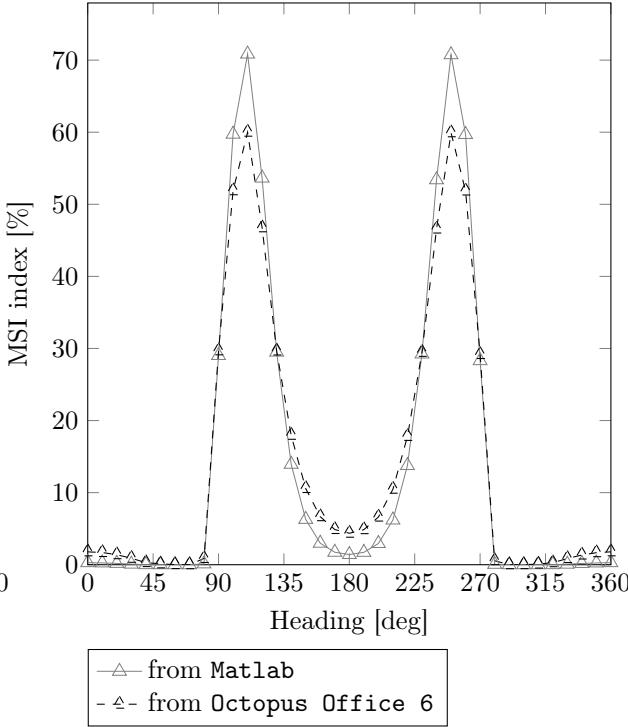
**Figure B.8:** Comparison between slamming rates at 40 kn speed in perfectly long crested seas, from Matlab and Octopus Office 6.

$v = 40 \text{ kn}, H_s = 3.1 \text{ m}, T_z = 4.59 \text{ s}, T_p = 5.9 \text{ s}$



**Figure B.9:** Comparison between rate of MII in engine room 3 at 40 kn speed in perfectly long crested seas, from Matlab and Octopus Office 6.

$v = 40 \text{ kn}, H_s = 3.1 \text{ m}, T_z = 4.59 \text{ s}, T_p = 5.9 \text{ s}$



**Figure B.10:** Comparison between MSI index in the CIC at 40 kn speed in perfectly long crested seas, from Matlab and Octopus Office 6.