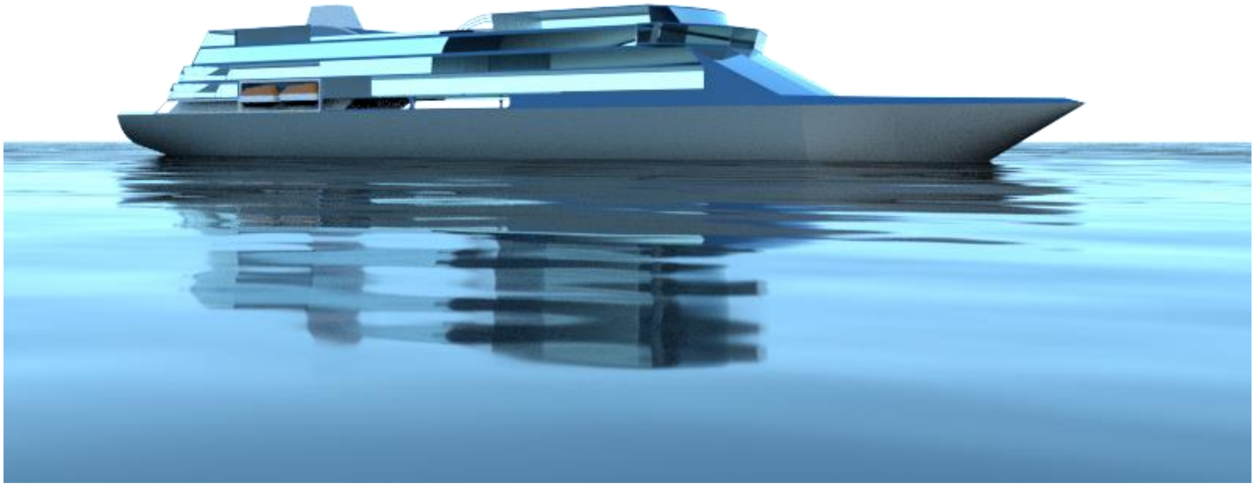
Aalto University School of Engineering
Department of Mechanical Engineering
Marine Technology
MEC-E2004 – Ship Dynamics



Frostisen

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Assignment 1

1.1 Operational Profile

A ship's operational profile determines the power load within a ship during a trip—from port to port, or in the case of a cruise ship, through the itinerary of that cruise. In our case, Frostisen will not have 1 set route but a series of routes that change throughout the year. There will be a set of cruises in arctic regions, and a set in Antarctic regions, as well as a yearly journey south and a yearly journey north. This means that Frostisen must be designed to withstand environmental conditions in the Arctic, Antarctic, and crossing the Atlantic. There will be itineraries mainly along the coast of Norway, in Svalbard in the north pole, Iceland, and Denmark. The trip north-south will include stops in the UK and Brazil. The normal South American itineraries will include Chile, Argentina, and Antarctica.

In technical terms, this means that we need to study the sea states likely to be found in different regions. Frostisen's lifetime will be in the Norwegian Sea, the North Sea, the Atlantic, the Scobia Sea, the Chilean Sea, and the Weddel Sea. The Antarctic cruise includes going through the Drake Passage, which has notoriously rough seas. The environmental effects of these areas can be seen in the waves, wind resistance, and ice. They effect the dynamics specifically by creating motions on the ship. The rolling motion can be countered by fin stabilizers. Ice is also an important environmental factor to consider in the dynamic analysis of our ship because ice will not only create resistance on the hull but might cause mechanical problems in the bow thruster.

The ice expected in the arctic and Antarctic environments will be minimal, as Frostisen will only have a Polar Class 6 which is only suitable for summer to autumn operation in first year ice. It does not have ice breaking capabilities, only ice strengthened hull, so in case of heavy ice, the itineraries move farther from the poles and in the autumn, switch hemispheres. Due to the environments, Frostisen will still encounter minimal ice for around 3 months per year. Normal operation of Frostisen will be itineraries of 5-10 days, up to 29 days for north-south hemisphere trips. Her capacity is 420 persons maximum.

Frostisen's operational profile is shown below. Figure 1 shows the route used to analyze the power requirements for a normal arctic cruise. The route is from Oslo to Longyearbyen with two stops at Bronnoysund and Tromso. Total cruising time is 5 days and 4 hours, and both stops are 4 hours long and the total distance is 1830 nautical miles. Figure 2 shows the operational profile associated with this itinerary. The operational profile is given in terms of a percentage of total load capability. The total load expected from this average itinerary does not exceed 45%. This was found in "normal" expected conditions and does not account for extreme weather or ice. The operational profile follows the trip to and from 4 ports.

Figure 1.1-1: Sample itinerary in Norway.

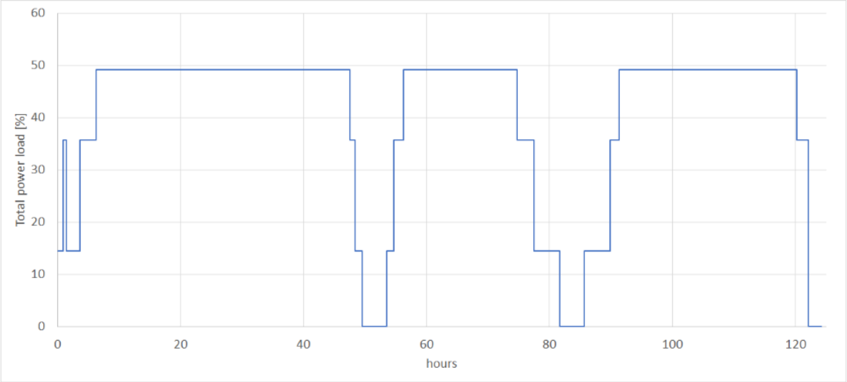


Figure 2: Operational profile given in percentage of power per hour of the sample itinerary.

The dynamic requirements based on the operational environments will include the need for fin stabilizers and bow thrusters. Frostisen will need good maneuverability in small ports, including many ports that are in Norway's fjords and will include some tight passages and turnaround areas. As mentioned, Frostisen will encounter rough seas in the Drake Passage and arctic area, so fin stabilizers are the best solution to controlling the motions. The following sections of this report will detail the maneuvering machinery: azipods, a bow thruster, and fin stabilizers.

1.2 Maneuvering Machinery

1.2.1 Azipods

The powering requirements were estimated from NAPA. The calculations used Holltrop method 84, 82, 78, and the Hollenbach method, and resulted in a maximum estimated power need of 18585 kW. The maximum speed of Frostisen is designed to be 21 knots, with a maximum propulsion power of 13,100 kW. This value was used to select propulsion. Azipods were chosen as the propulsion method because of their fuel consumption efficiency, as fuel reduction and environmental considerations are key to our design. As Frostisen is a luxury cruise vessel, the high initial cost is also a secondary consideration. Azipods also connect with electric system, making them optimal to use with both the engines and battery system. They also reduce noise and are safer than traditional propulsion, making them popular for passenger vessels. In terms of dynamic requirements, Azipods also have increased maneuverability, with full rotation capability and good controllability.

2 ABB Azipod DO1600P with a power of 7.5 MW each using 4 meters diameter propellers with 3 meters of pitch. The achievable speed is 22 knots. Our design speed is 17 knots, so the Azipods fit within the design. Also comparing to the maximum speed of 21 knots with propulsion power of 13,100 kW found in the power estimation of our hull, the chosen Azipods slightly exceed these limits making it an ideal choice. One consideration in this design though, is the usage of the calculation methods for the power and propulsion calculations in NAPA—these calculations are based on traditional propulsion, and Azipods may not fit perfectly into this model. This inconsistency is marked as an uncertainty in our resistance calculation that we will keep in mind in our design.

Figure 3 shows a rendering of the selected Azipods from ABB. ABB also provided schematic drawings of the Azipods, which were used to correctly size them in AutoCAD to add to our GA. Figure 4 shows the profile and plan views zoomed into the Azipod section. The aft peak bulkhead has been moved aftwards to create more vertical clearance for the Azipods. There is still a watertight section aft of the Azipod machinery which cooperates with the rules, requiring a watertight compartment to separate propulsion from the aftmost section of the ship. The plan views show Decks B and C, as the Azipod machinery extends through 2 deck levels.

Figure 3: Azipod rendering.

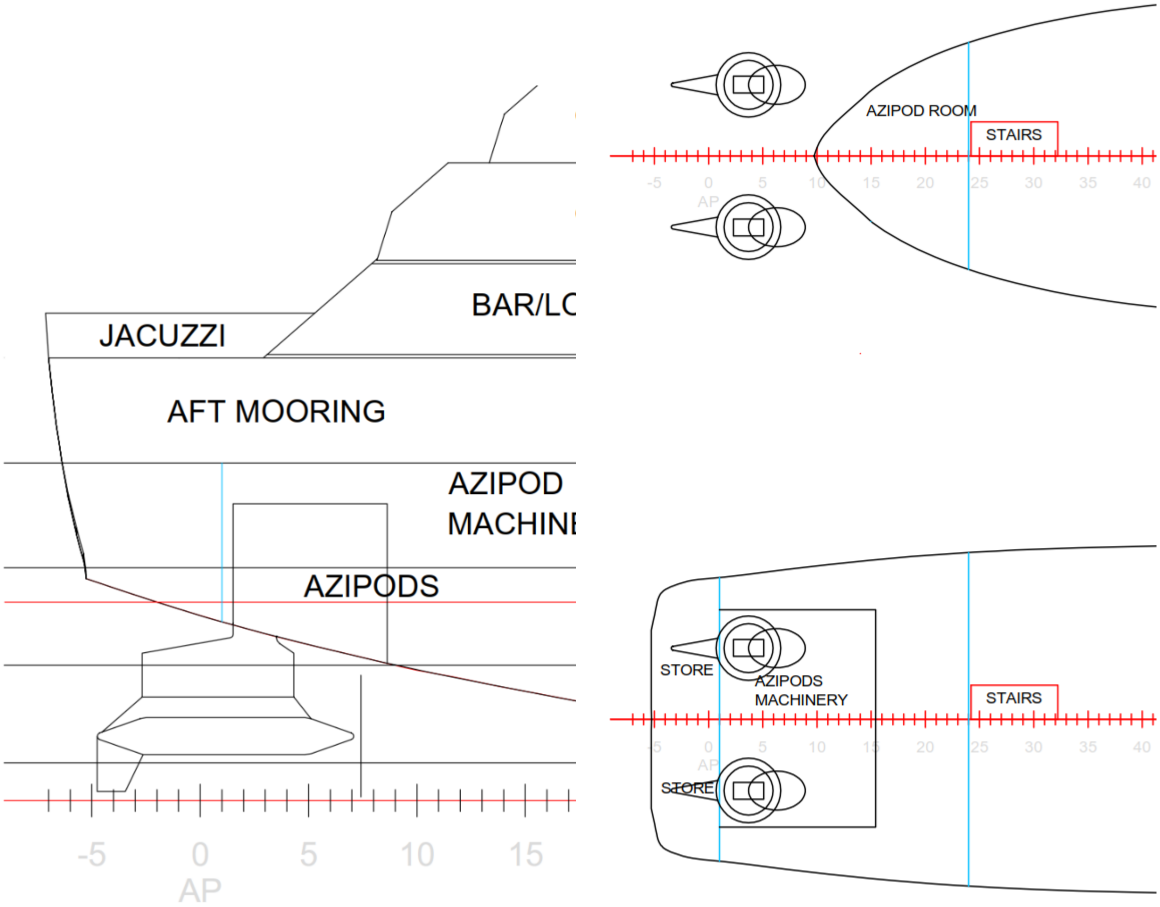


Figure 4: Azipod placement in the GA, profile and plan views. Azipod machinery room is on Deck B.

1.2.2 Motion Reduction Systems (Fin Stabilizers)

Frostisen is a luxury cruise vessel planned to make voyages to the Arctic and Antarctic circles. The route to the Antarctic circle goes through Drake Passage, which is the body of water between South America's Cape Horn and the South Shetland Islands of Antarctica (see Figure 1.2-1). Drake Passage is considered one of the roughest seas in the world. Since the ship is a luxury passenger ship and to increase passenger comfort, solutions to reduce ship rolling motion are needed. We selected active fin stabilizers for roll motion reduction.

Figure 1.2-1: Drake Passage connects the southwestern part of the Atlantic Ocean with southeastern part of the Pacific Ocean.

Retractable active fin stabilizers are expensive to install and maintain and they require extra space to house them. However, this investment can be justified as luxury cruise vessels require high level of comfort for passengers. Additionally, stabilizing fins can produce thrust without compromising their stabilizing purpose, which can lower fuel consumption by 1% (Matusiak & Rautaheimo, 2017).

Commercially available SKF Retractable Fin Stabilizers Type S600 were chosen for the vessel (see Figure 1.2-2). Fin area is about 10 m^2 and dedicated space was allocated amidships for the fins and their machinery in the double bottom and deck A. Figure 1.2-3 and Table 1 show space reservation for the system.

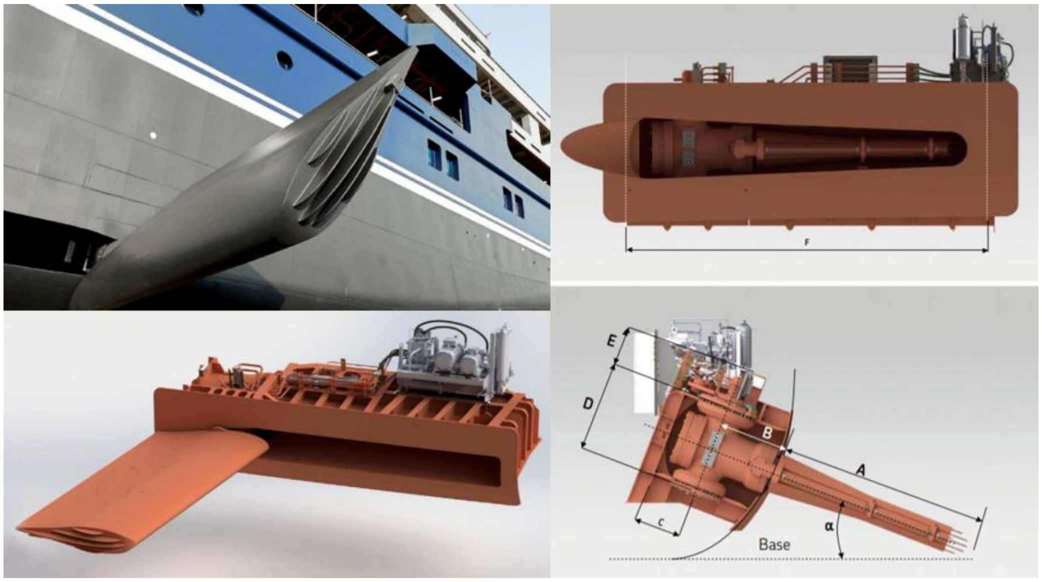


Figure 1.2-2: SKF Fin Stabilizers Type S

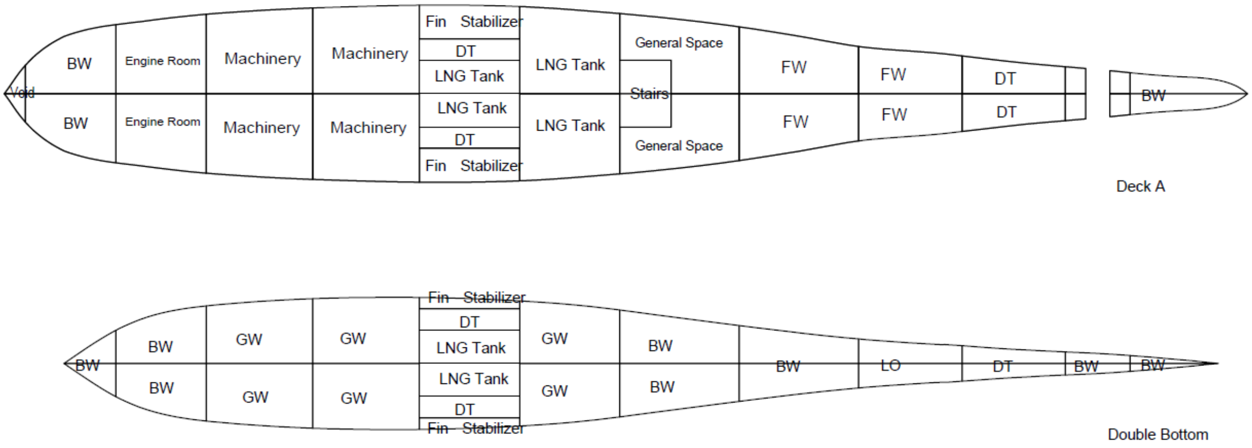


Figure 1.2-3: Space for SFK fin stabilizer system in GA.

Purpose	Location	Area (m^2)	Volume of Compartment (m^3)
Fin	Double bottom frames 79-90	18.90	20.43
Fin machinery	Deck A frames 79-90	40.01	108.03

Table 1: Space reservation for SKF fin stabilizer system.

1.2.3 Bow Thruster

The operational area of Frostisen includes visiting and mooring in several ports, some that are rather small. Therefore, it is highly important that the concept ship is capable of performing 180° turns where the space is limited. Also, the speed of performing these turns is crucial and need to be optimized to be as short as possible. Because of these characteristics of Frostisen, it is decided that the vessel need to be equipped with Wärtsilä’s WTT-16 transverse thruster. Figure 1.2-4 illustrates the Wärtsilä’s transverse thruster. The technical properties of the specified bow thruster are presented in the table below.

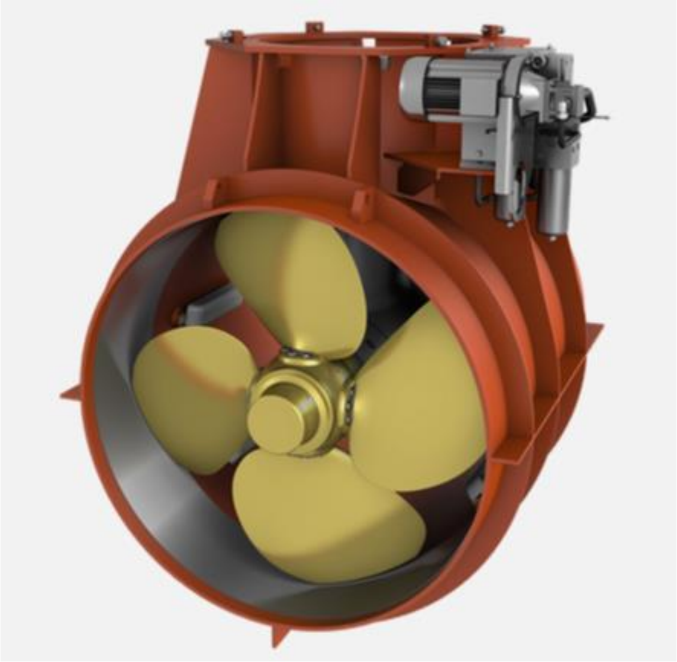


Figure 1.2-4 Wärtsilä's Transverse Thruster.

Thruster type	Maximum Power, Manoeuvring AUX [kW]	Dynamic Positioning, DP [kW]	Propeller Diameter (D) [mm]	Length [mm]	Weight [kg]
WTT-16	1650	1475	2200	2115	11300

Table 2 Technical properties of WTT-16 Transverse Thruster.

The purpose of utilizing transverse thrusters, also known as bow thrusters, is that they provide a side force, or transverse thrust that supports the mooring operations or position keeping of the vessel. When it comes to standard product configuration, Wärtsilä lists that bow thrusters utilize controllable pitch (CP) or fixed pitch (FP). Generally, the remote-control system includes propulsion control cabinet such as thruster room and also control center in the bridge. In a case of CP propellers this is for standard and for the Frostisen the CP propellers is the qualified choice. (Wärtsilä, 2017) By implementing WTT-16 bow thruster into Frostisen, it enables enhancing the turning capabilities of the vessel.

The placement of bow thruster is on Deck A. The bow thruster is located aft of the fore peak bulkhead. The space reservation is illustrated in the Figure 1.2-5 and Figure 1.2-6.

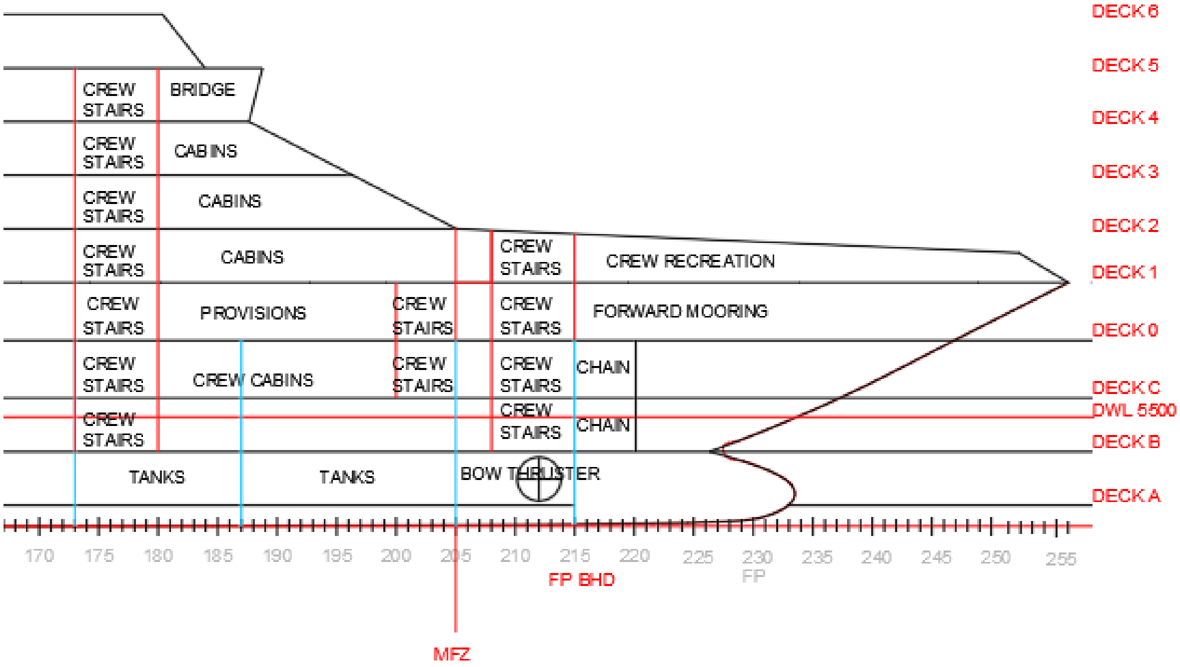


Figure 1.2-5: Location of the Bow Thruster.

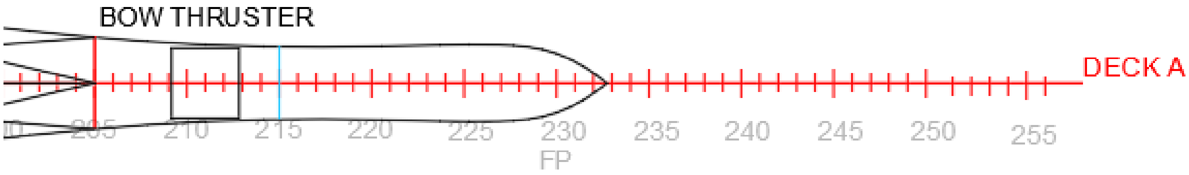
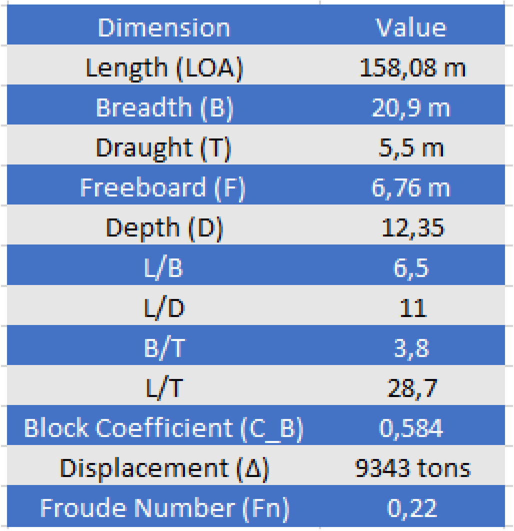


Figure 1.2-6: Bow Thruster is located on Deck A.

1.3 Features of Hull form that affect Ship Dynamics

When it comes to hull features, we recognized few certain aspects of Frostisen that need to be considered. Overall, the hull is designed to operate in open waters. As discussed before, Frostisen will face some ice conditions, however, the expected ice in the arctic and Antarctic environments will be minimal. The ship is not designed to use as an icebreaker. The main dimensions of Frostisen are presented in the table below.



Dimension	Value
Length (LOA)	158,08 m
Breadth (B)	20,9 m
Draught (T)	5,5 m
Freeboard (F)	6,76 m
Depth (D)	12,35
L/B	6,5
L/D	11
B/T	3,8
L/T	28,7
Block Coefficient (C_B)	0,584
Displacement (Δ)	9343 tons
Froude Number (Fn)	0,22

Table 3 Main dimensions of Frostisen.

The hull form of Frostisen is also illustrated in the Figure 1.3-1 The hull form is designed considering that there needs to be a balance between low resistance and adequate stability to ensure safety and luxurious passenger-friendly experience. Consequently, the designed hull form is long and narrow, more of a slender hull. This ultimately have influence on the ship's stability, and it needs to be checked further. The block coefficient of Frostisen is also rather low compared to regular cruise ships. Length of the hull has direct correlation to response to waves such as pitch, heave and resonance. Higher value of block coefficient would result in higher resistance although, it could also decrease the unwanted motions in waves.

Taking into account the propulsion system of Frostisen, it is necessary that the bottom of the stern is designed in a specified way. Since Frostisen would be utilizing Azipod thrusters, there are few key elements that must be considered in the hull form design. The electric podded azimuth thrusters demand that the bottom of the stern is as flat and horizontal as possible. That origins from the fact that the mounting of the propulsion system is possible only to flat surface. However, in the current state of hull form design, the stern of Frostisen doesn't answer these requirements. Thus, the situation is now recognized, and the re-designing is done in later phase of the ship design process. Ultimately, the flat surface at stern is prone for slamming in high waves. Homogenous inflow to propellers is ensured, since the pods move the propellers further away from the hull.

Freeboard of Frostisen is 6,76 meters and it's adequate for a cruise ship. L/T ratio is quite high and that results in vulnerability to resonance with shorter waves, because it leads to greater amplitudes in short waves. In addition, a vessel with high L/T-ratio is more prone to slamming phenomena.

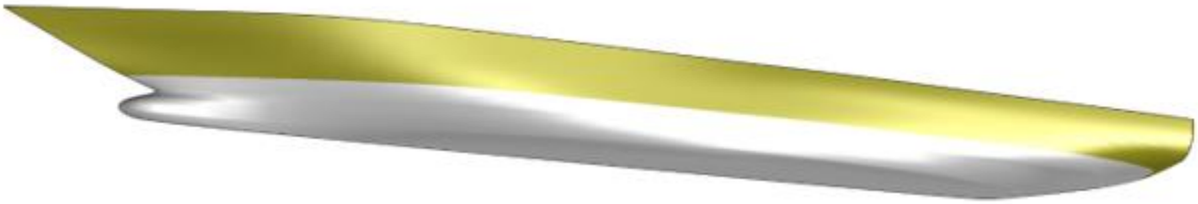


Figure 1.3-1: Hull form of Frostisen created in Delftship.

The vessel also has a bulbous bow, and quite clearly that is to utilize effective drag. The WTT-16 bow thrusters are also considered to be installed in the bulb. The main purpose of utilizing bulbous bow is that it shifts the bow wave forward away from the hull for a smaller resistance. A bulbous bow is a protruding bulb at the bow of the vessel that is located below the waterline. The main function of bulb is that it modifies the way the water flows around the hull. Consequently, bulb reduces drag and therefore, increases speed, range and fuel efficiency. Bulbous bow also tends to increase buoyancy of the forward part of the vessel. Ultimately, this reduces the pitching of the ship to a small degree. The bulbous bow is optimized for cruising speed in average short-wave conditions, where it usually reduces motions. However, in longer wave conditions, it can lead into increased motions.

1.4 Reflections on Scientific Articles

The main purpose of stabilizing fins is to dampen roll motion of ships in waves. Matusiak & Rautaheimo (2017) investigated whether stabilizing fins can also produce thrust by extracting energy from waves. The paper studied simulations for three different arrangement of fins. The angle of attack was controlled in a way that maximizes the horizontal component of the force (thrust). It was found that in long waves, one pair of fins located at midship can generate close to 2% of thrust power needed to propel the ship. Two pairs of fins located towards the fore and aft parts of the hull can generate up to 7% of thrust power needed. Thrust generated by fins increases with wave height.

These findings could be interesting to implement in an expedition cruise vessel like Frostisen. As the vessel is expected to encounter rough seas in its operational profile, smart control of the angle of attack of its pair of fins may produce 1-2% of thrust power. This can have significant economic benefit by reducing fuel consumption. An interesting application of this research paper requires knowledge of control engineering and perhaps artificial intelligence that can detect and predict wave characteristics in real-time and adjust the angle of attack to maximize thrust power produced by the fins while not compromising their roll damping function.

In lecture slides, pros and cons of stabilizing fins were studied. It was understood that stabilizing fins can’t totally solve the problem of rough seas and they are costly to install and maintain. They also require additional space in the hull. Despite these cons, Matusiak & Rautaheimo (2017) paper was one of the reasons that motivated our team to choose fin stabilizers as a roll damping mechanism as opposed to other simpler solutions like bilge keels.

In “Ship Maneuvering: Past, Present, and Future,” Skjetne discusses the development of maneuvering technology. One such development is dynamic positioning, which controls surge, sway, and yaw using azimuth and tunnel thrusters. The dynamic positioning system takes input from a hydrodynamic model simplified into a linear model for near zero speed. This model limits the usage of such a system to situations in which the ship is meant to be stationary.

The future of maneuvering technology, unlike dynamic positioning, aims to control the path of the ship at the desired speed. Where dynamic positioning now only stabilizes the ship at zero speed, maneuvering technology will develop to stabilize the ship in transit. The maneuvering problem is concerned with putting the ship along a path, geometrically, and simultaneously controlling the speed along that path. At higher speeds, the hydrodynamic model must be non-linear. A ship model involves an inertia matrix, damping force, and forces/moments applied by propulsion and steering. The model is necessarily complex and contains many uncertainties and debatable assumptions. The maneuvering machinery are called “actuators” in the model, and it is said to be “fully actuated” if the forces and moments affecting surge, sway, and yaw, are all controlled within the model. Current research has indicated that there are usable models of fully actuated and possible under actuated maneuvering control systems that can be commercially produced. The article also briefly states the future challenges in maneuvering control design, including the design of systems that can handle extreme weather.

The article relates to Frostisen’s design because it gives a good explanation of the technology available to assist in maneuverability. Dynamic positioning is one good option available on the market currently and would be well suited for our design. Frostisen’s usage of Azipods and bow thruster make a dynamic positioning system easily implementable to better control motions. This is especially appealing for a luxury cruise ship to increase passenger comfort.

Assignment 2

2.1 Route and Wave Conditions

As discussed in the previous chapter Operational Profile, Frostisen will not have just one specific sea route. There will be a series of different routes that change throughout the year. Consequently, defining certain water depths and seasonal variations of wave conditions to all of the conditions that Frostisen will face is a major task. Therefore, it was decided that the route showed in Figure 1.1-1: Sample itinerary in Norway., is also used to analyze these different conditions.

However, an attention is paid to other environmental effects in different operation areas. The cruise route in the Antarctic includes going through the Drake Passage which is quite famous for its rough wave conditions. These wave conditions are rather examined in the following chapter of Extreme Events. Frostisen is ultimately needed to be able to withstand environmental conditions in the Arctic, Antarctic and crossing the Atlantic. The structural requirements of the hull are more accurately considered in the Ship Structures -course.

2.1.1 Operation in the Arctic Ocean

When it comes to itinerary in Norway, the cruise takes place from Oslo to Longyearbyen. The route between these ports considers travelling through the North Sea, the Norwegian Sea and sometimes visiting the Barents Sea. The sample route is presented in the following figure.

Figure 2.1-1 Arctic route of Frostisen goes through different seas.

The water depths of specific cruise route vary. The Norwegian Sea is the major sea area in that route, and it is outlined in the following Figure. The water depths are in between 200 and 1000 meter as the route follows the coastline of Norway. The North Sea is rather shallow, and the depths of that area are in a range of 0-200 meters. As mentioned, the Barents Sea can be a part of Frostisen's route but in most cases, it is not as it extends the route to southeastern side of Svalbard. However, when it comes to water depths, they are not that different in the Barents Sea either. In most parts the Barents Sea has a depth of 200-1000 meters. The surroundings of Svalbard in the southeastern sea area are also shallower as the water depth in this certain area is less than 200 meters. Consequently, water depths in the specific area are roughly divided into four categories and presented in the figure below.

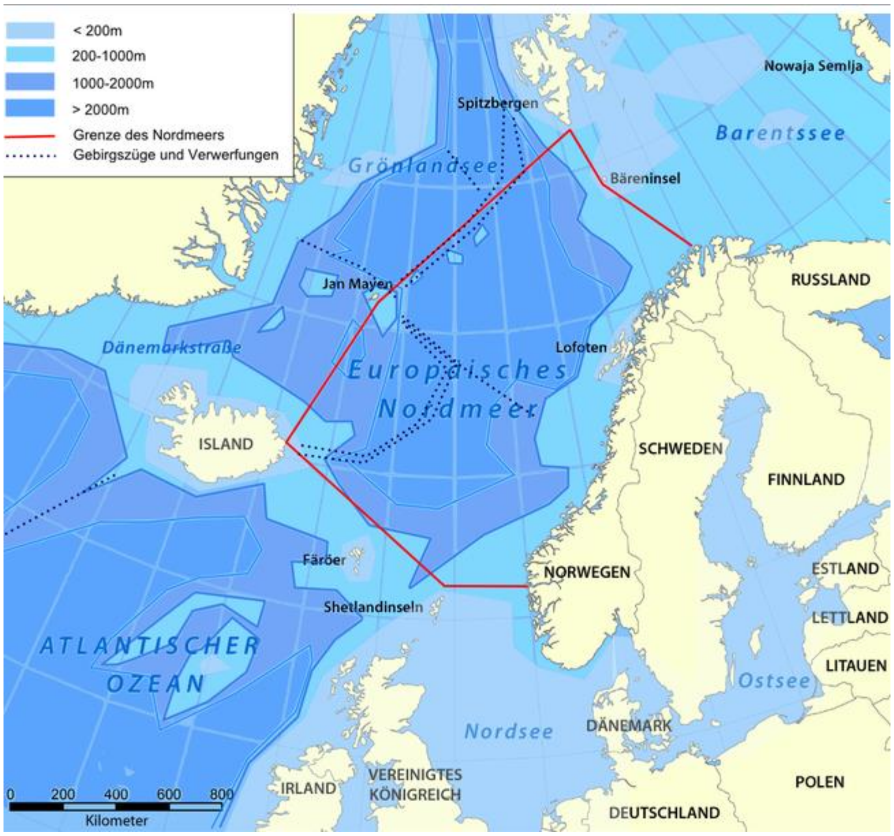


Figure 2.1-2 Water depths on Arctic route.

The operation in the Arctic Ocean is being organized in the summer months and therefore, the sea temperature is high. The table below presents the average sea temperatures in the Norwegian Sea. As it can be noticed, the summer months are much warmer, and the temperature rises above 12 °C.

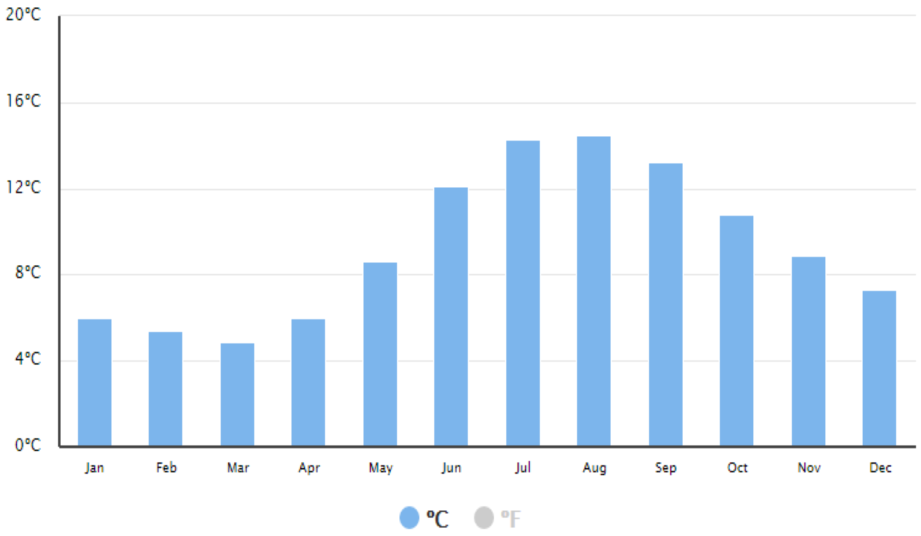


Table 4 Sea Temperatures in the Norwegian Sea

When it comes to wave conditions in the Arctic itinerary, the journey of Frostisen travels close to coastline. Therefore, the wave height doesn't rise too high. Generally, wave height varies between 2-4 meters. The North Sea and the Norwegian Sea share rather similar characteristics when considering the wave height of these areas.

2.1.2 Operation in the Antarctic

The operation of Frostisen in the Arctic area is considered to be organized during the summer months. After that, Frostisen is supposed to travel across the globe and Atlantic to South America where it starts its operations to Antarctic. The route on the other side of globe includes travelling through Drake Passage. Drake Passage is a water body between South America and Antarctica, specifically it is located between the southernmost land point of the continent, Cape Horn, and South Shetland Island in Antarctica. The Drake Passage is showed in the figure below.

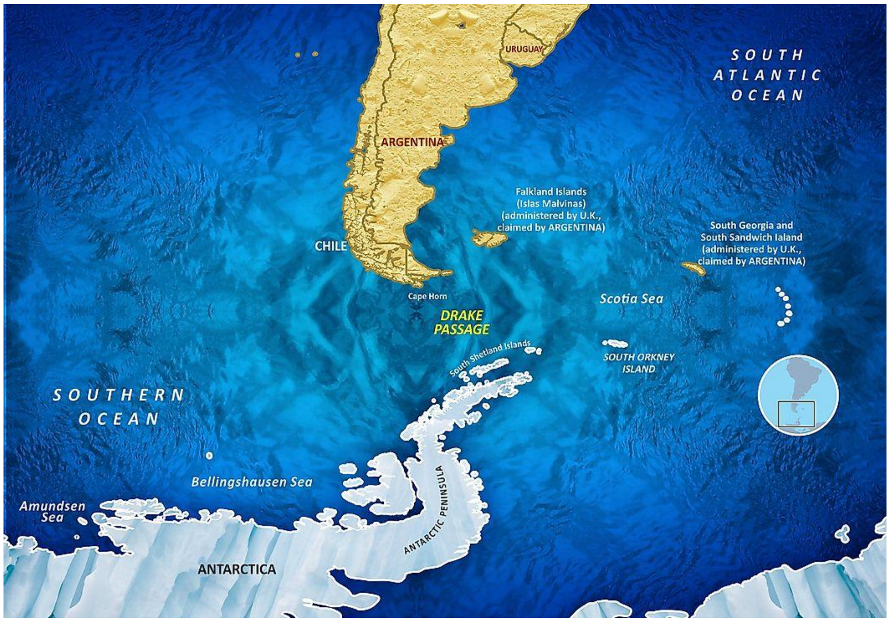


Figure 2.1-3 Drake Passage

The sea conditions can evolve very dangerous as the currents at that certain latitude meet no resistance from any landmass. Consequently, the wind speed and wave height make the circumstances in the area difficult. Wind speed regularly vary between 5 to 30 knots, with wind gusts reaching up to 40 knots. Windy.app has presented its historical data on wind speeds in Drake Passage and statistics are shown in the table below (Windy, 2021).

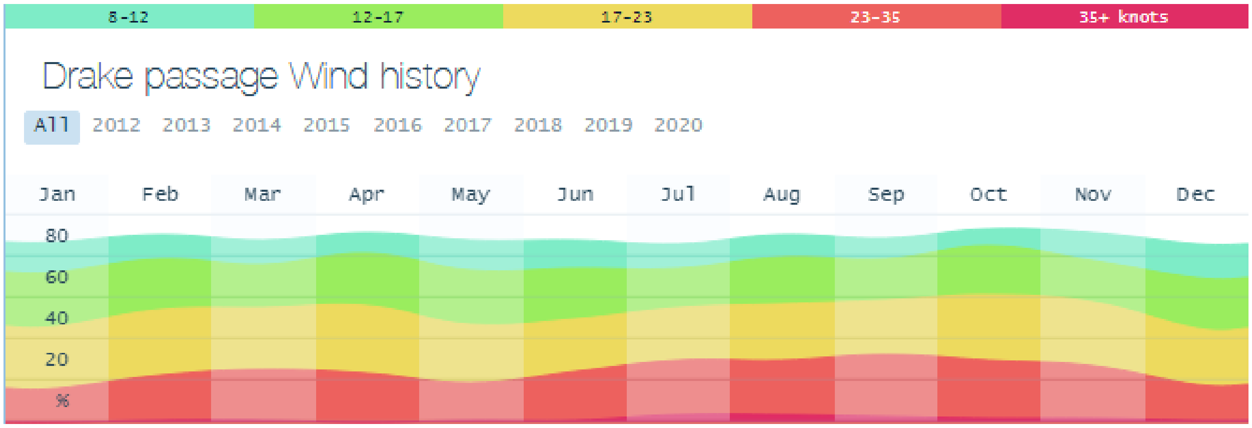


Table 5 Drake Passage Wind history

The data shows that wind varies a lot in the area. The speed is divided into five slots and almost 20% corresponds to all of those. However, in every month there is occasions where wind speed reaches dangerously high point. This of course, have an influence on the waves. The wave conditions ultimately also vary a lot in the area. Although, Drake Passage is famous for its rough seas and storms. On a calm weather the wave height is in range of 2 to 5 meters. Considering the rougher circumstances, according to Saildrone, it was recorded that there have been 8.8-meter waves on a 13-second interval (Saildrone, 2020).

As it can be seen from the wind history in Drake Passage, the seasonal variations have something to do with the conditions. However, the differences between different months is not that significant. The voyaging of Frostisen in the Antarctic area would be organized during the winter months. Wind speeds don’t reach more than 35 knots in the December and January as often as in the November, February and March. Consequently, rather rough wave conditions are also met during the late fall and early spring seasons.

The Drake Passage is much deeper than the route of Frostisen in the Arctic area. The following figure presents the profile of Drake Passage as also the salinity and temperature curve. Here, it can be noticed that the water depth is below 2500 meters in major part of the route. Only closer to land, the water is shallower.

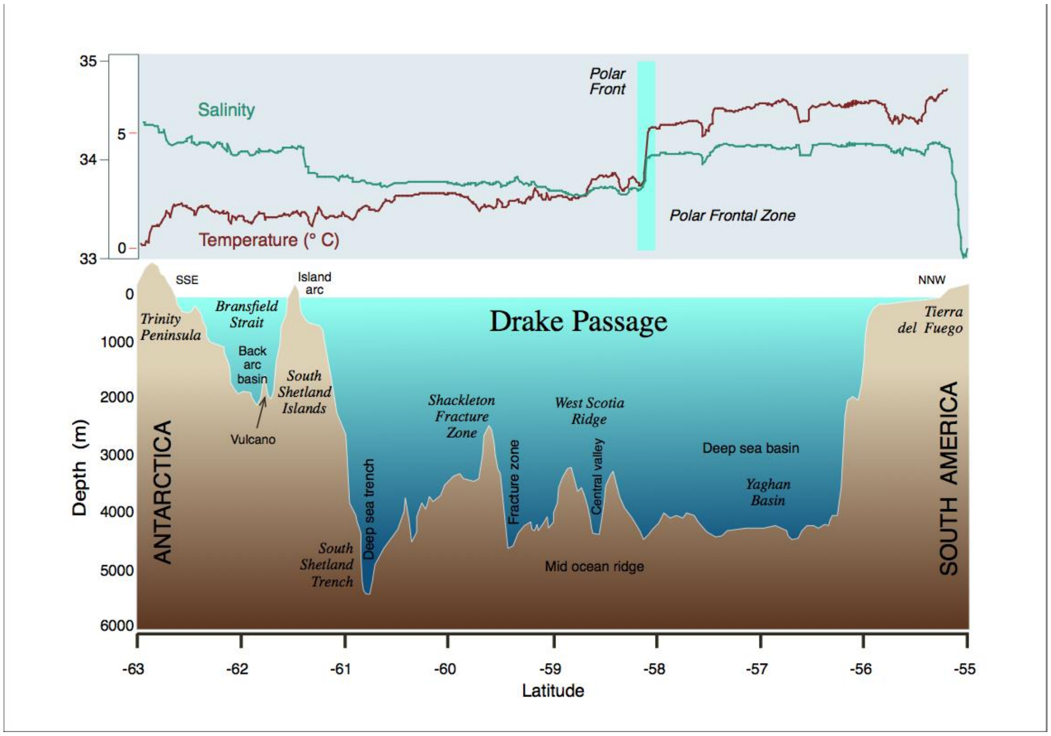


Figure 2.1-4 Drake Passage Profile

2.2 Wave Types

Stokes wave theory is most suited to model waves in deep and intermediate water depths while Cnoidal wave theory is more suited to shallower waters. Based on discussion in section Route and Wave Conditions, Frostisen’s voyage can be sectioned based on water depth along with suitable wave theories used to model waves in these areas. Figure 2.2-1 and Figure 2.2-2 below show water depth in a typical voyage and corresponding wave theories.

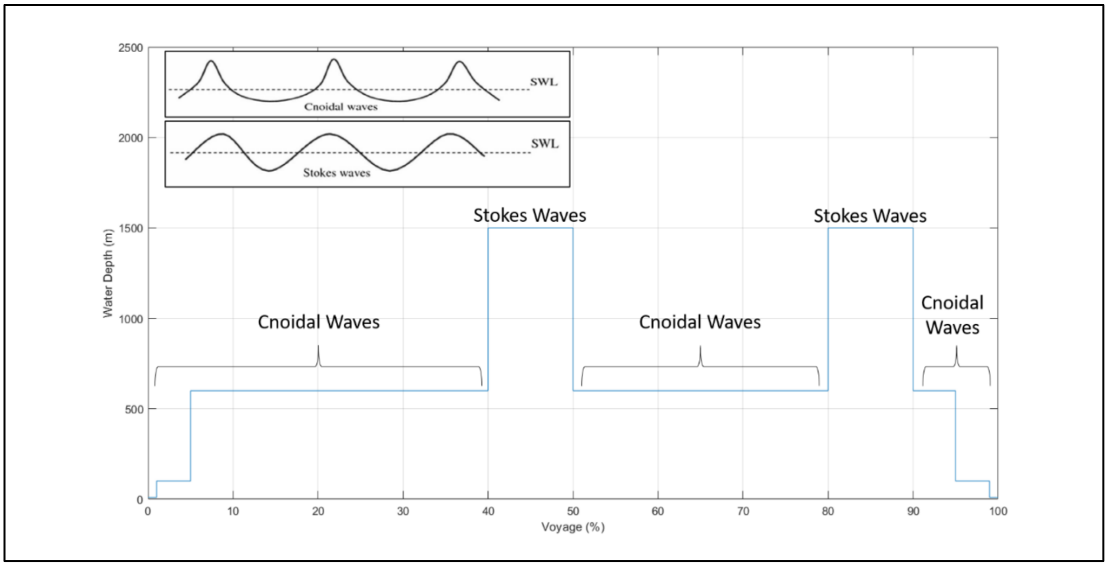


Figure 2.2-1: Water depth and suitable wave theories to model waves (Arctic voyage)

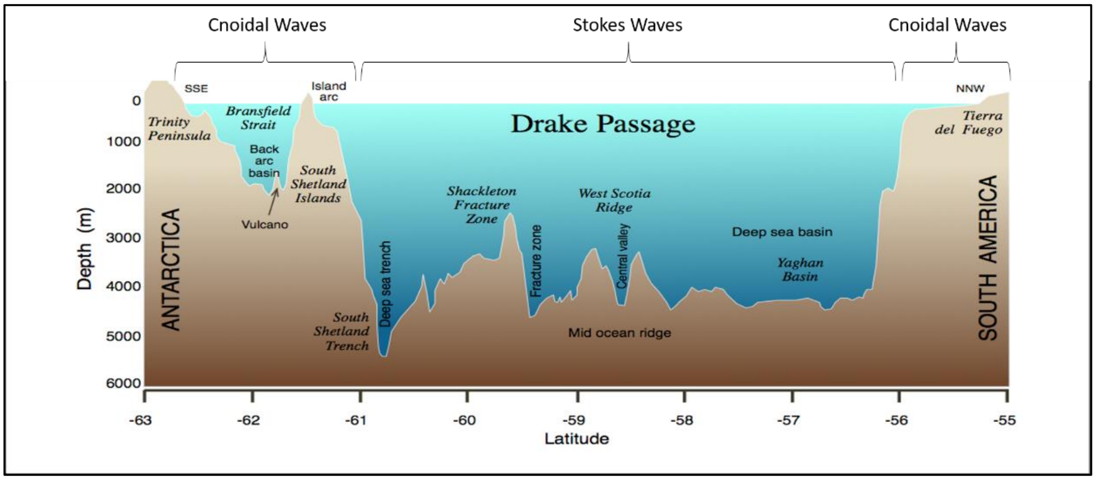


Figure 2.2-2: Water depth and suitable wave theories to model waves (Antarctic voyage)

2.3 Wave Spectra

The sea is made up of the summation of individual sinusoidal waves that compose an irregular signal. Although the waves are random, the statistical properties can be extracted from the signal by recording the wave data for a time interval. The time domain data is transformed to the frequency domain. In the frequency domain, the data can be idealized into spectral models of idealized wave spectra. When an idealized sea spectrum method has been selected, it is then modeled using operational data. Modeling wave data as a spectrum is useful in analyzing motions of a ship. In this assignment, we must determine from our operational area which types of sea state is most suitable.

There are 3 common types of wave spectra. The first 2 come from the Pierson-Moscowitz spectra. They are the ISSC and the ITTC spectra. The third wave spectrum is the Joint North Sea Wave Project (JONSWAP) spectrum. The Pierson-Moscowitz spectrum is based on fully developed seas, meaning that the wind has blown the waves from such a distance that the waves are fully developed. The ITTC spectrum takes one parameter as input, the significant wave height. The ISSC spectrum takes 2 parameters as input, the significant wave height and the characteristic wave period. Significant wave height is defined as the mean highest third of the wave heights in that sea. The JONSWAP spectrum includes seas that are not fully developed. The JONSWAP spectrum is therefore more suitable for areas that do not include vast amounts of open sea, such as channels and bays.

The areas that we will be analyzing are the north and south poles. Frostisen will otherwise have 2 crossings per year between the poles, but these crossings cover such a large area and will only be done infrequently that they do not cover the scope of this course. We will focus on designing to the harshest and most common situations: the normal operation in the Norwegian Sea, Scotia Sea, and Weddel Sea, and the harshest conditions in the Drake Passage. The most suitable sea spectrum for these areas is the Pierson-Moscowitz spectrum because our operational area, especially the Drake Passage which will hold the most extreme cases for both operation and freak events, have fully developed seas. The Norwegian Sea also fetch limited, and is near the area which the JONSWAP spectrum was developed, so this particular area might benefit from using the JONSWAP spectrum.

The JONSWAP spectrum uses either wind speed and fetch, or significant wave height and period and fetch as input. The historical statistical data is given in terms of significant wave height and period. The equation to find a JONSWAP spectrum is:

$$S_\zeta(\omega) = B_j \bar{H}_{1/3}^2 \frac{2\pi}{\omega}\left(\frac{\omega_0}{\omega}\right)^4 e^{-\left[\frac{5}{4}\left(\frac{\omega_0}{\omega}\right)^4\right]\gamma^r}$$

The Pierson-Moscowitz spectrum uses wind speed as input. The following equation is used to model a Pierson-Moscowitz spectrum:

$$S_\zeta(\omega) = \frac{0.0081 g^2}{\omega^5} e^{-0.74\left(\frac{g}{W_{19.5}\omega}\right)^4}$$

The ITTC spectrum, however, may be more accurate, and can use statistically determined values of significant wave height and period as input. The ITTC spectrum is shown below:

$$S_\zeta(\omega) = \frac{1.25}{4}\left(\frac{\omega_0}{\omega}\right)^4 \frac{\bar{H}_{\frac{1}{3}}^2}{\omega} e^{-1.25\left(\frac{\omega_0}{\omega}\right)^4}$$

To model the sea states using the ITTC idealized spectrum, the significant wave height and period. These are obtained using global wave statistics. The zones for global wave statistics are shown in Figure 14 (Hogben et al. 1986).

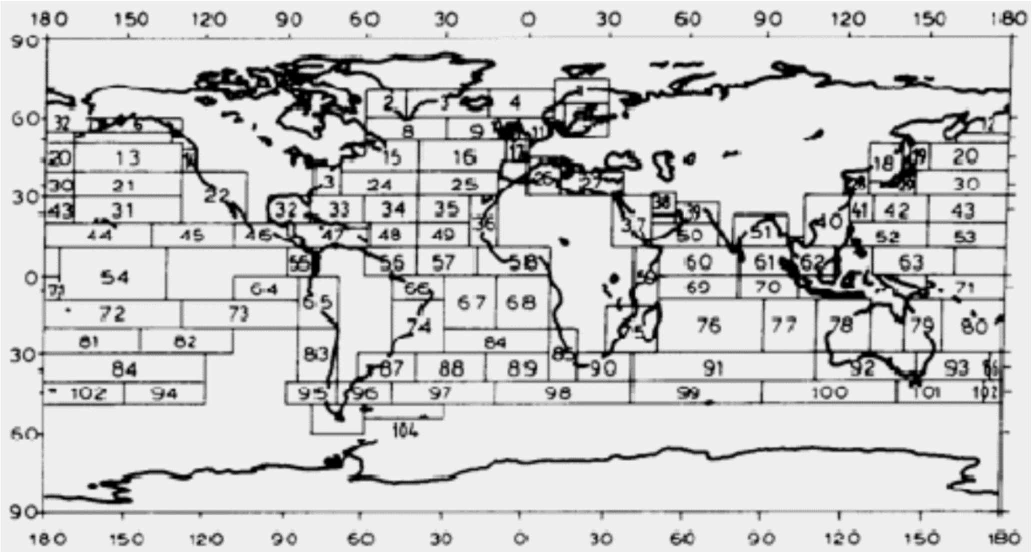


Figure 2.3-1:Global Wave Statistics

In the case of the Drake Passage, zone 104 is closest. Looking at the statistics for this area, the significant wave height and period are shown below. These were obtained from the article "Small scale open ocean currents have large effects on ocean wave heights" (Ardhuin, 2016). Global wave statistics were unable to be found at the moment, but this article provided estimates for harsh scenarios for now. The article gives a sample significant wave height of 4 meters with a period of 10 seconds. Those could be used as an example for a sea state likely to be found in the Drake Passage. The rate of occurrence of different sea states, harsh conditions, and freak waves must be determined for further analysis.

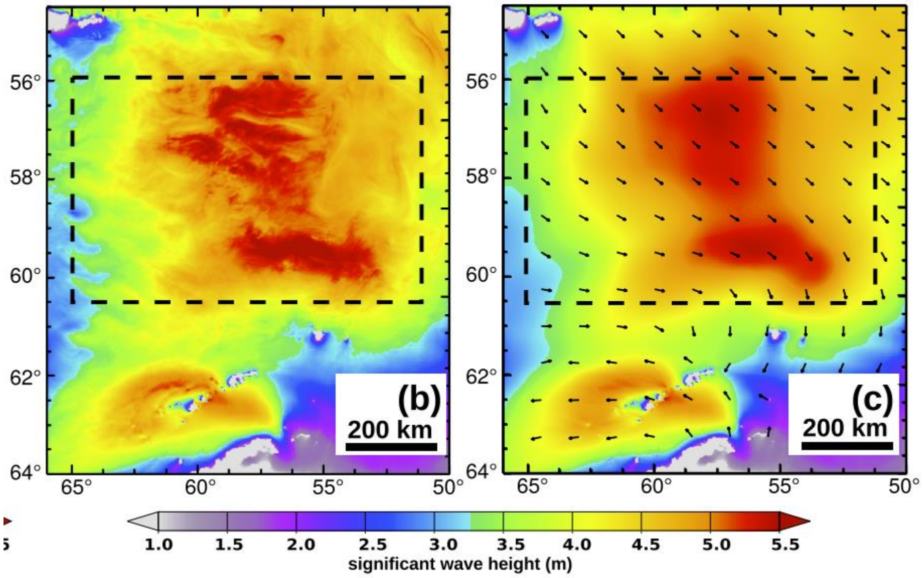


Figure 2.3-2: Significant Wave Height in Drake Passage (Ardhuin, 2016)

An example of a wave energy spectrum calculated using the sample significant wave height and period of 4 meters and 10 seconds is shown below using the ITTC method.

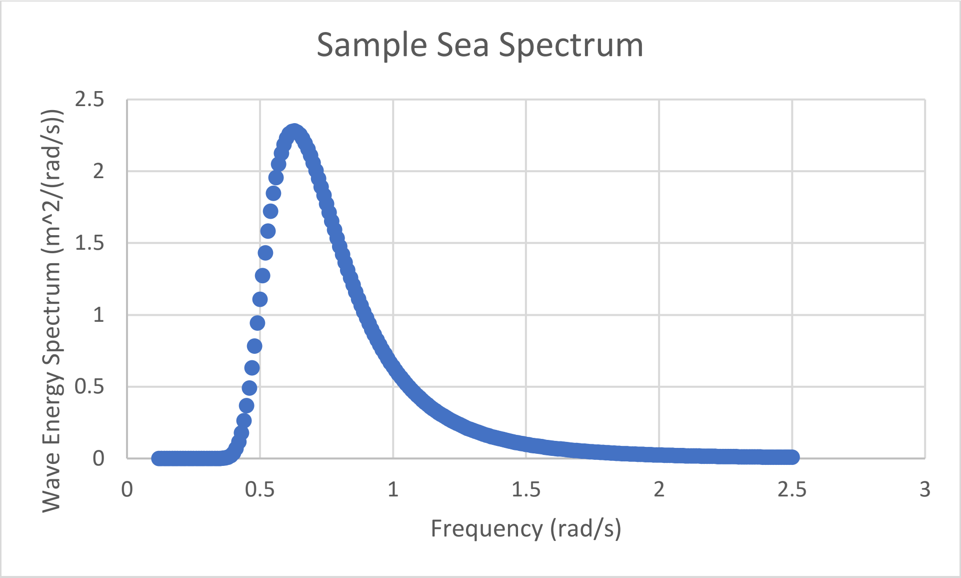


Figure 2.3-3: Sea Spectrum with Sample Parameters

This is a sea spectrum that would likely occur in the Drake Passage, but further statistics are needed for this class to determine the cases of sea spectrum that we will design Frostisen to in terms of motions and structural analysis. Historical sea statistics might be helpful here as they provide a probability of occurrence of certain significant wave heights and periods. However, these statistics also have problems with accuracy, as they are from the 1980s and since then, the behavior of the sea has changed due to global warming. The statistics also are only provided for large areas of sea, whereas we might want to predict behavior in a relatively small area, like the Drake Passage. An alternative to using historical statistics would be to research sea wave statistics from this area or to do our own analysis based on wind data.

2.4 Extreme Events

Sea waves are a random process which means that there can be extreme events that are difficult to predict beforehand. This applies to both of the operational areas of Frostisen. As the Frostisen is supposed to travel from north pole to south, there are likely more extreme events than discussed here. In this assignment, the two more traditional operational areas of Frostisen were considered, the Arctic and the Antarctic route.

When it comes to Antarctic route, it is rather exposed to extreme events. The Drake Passage is vulnerable to seismic activity and there have been several earthquakes recorded in the area. The following map shows the areas where recent earthquakes have happened. The magnitude of these earthquakes varies a bit, but in most cases, it is in a range of 4.5 to 5.4. (Earthquaketrack, 2021) This magnitude implies to earthquake effects that it is often felt but only minor damage is caused. There are still some stronger earthquakes recorded in the area with magnitude of larger than 5.5 but below 7. These events are classified as moderate or strong in the earthquake magnitude scale. Scale values below

6 but above 5.5, the damages are still rather slight, although with Richter value of 6-7, major damages can be caused to buildings. In case of earthquakes also a risk of tsunamis is present.

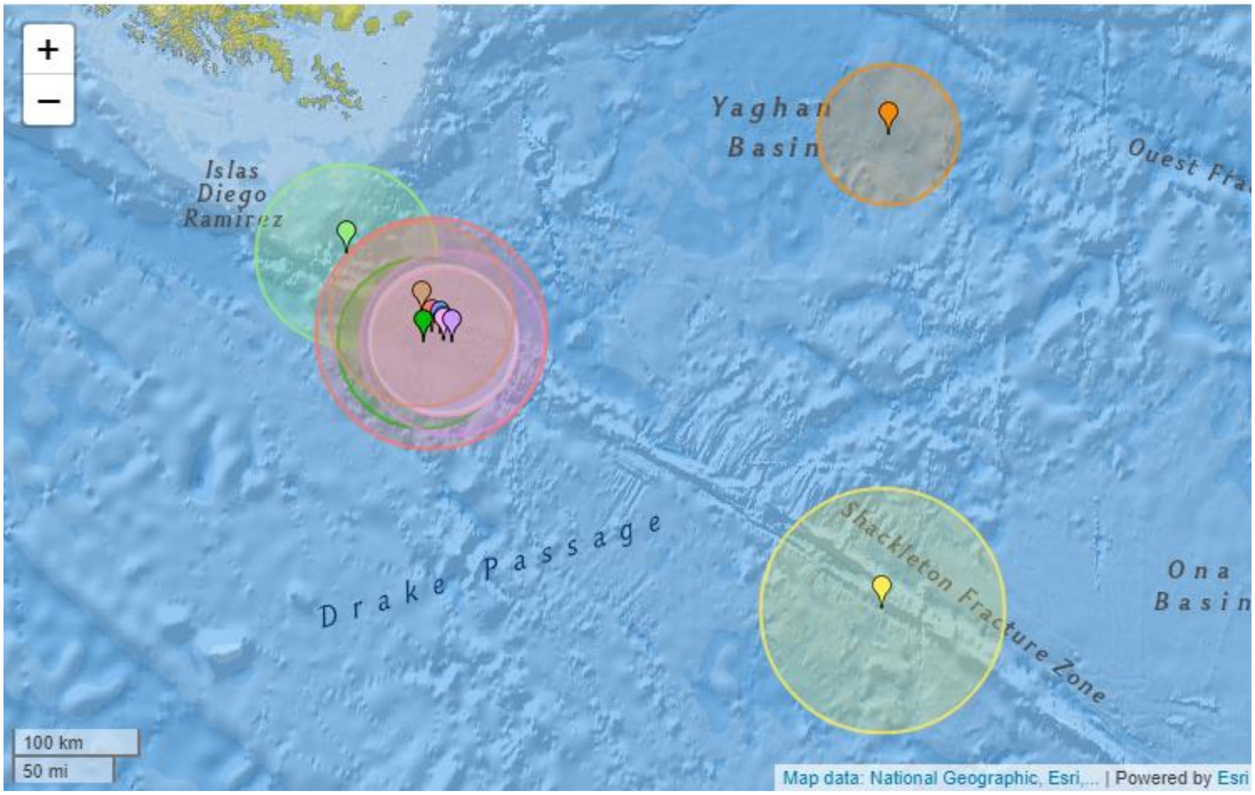
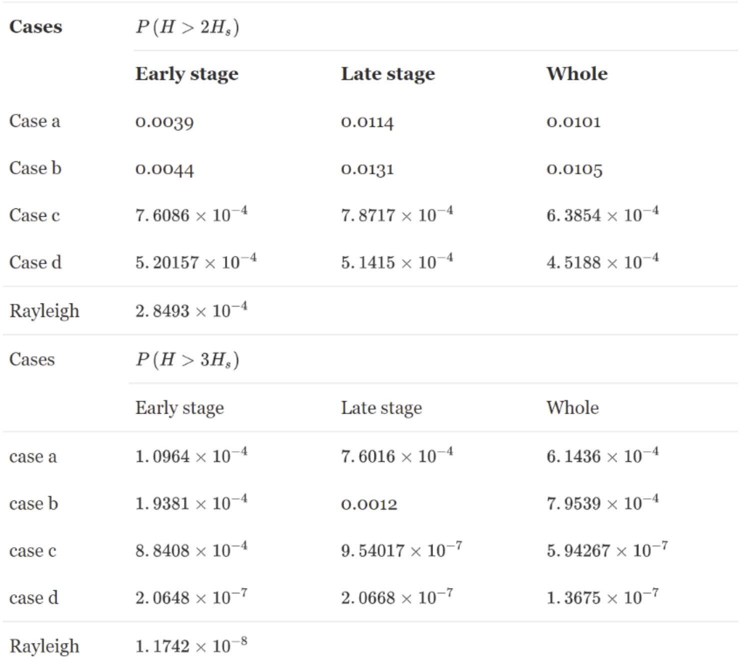


Figure 2.4-1 Recent Earthquakes near Drake Passage

Freak waves are extreme waves that can happen in sea states. Their wave height is at least two times the significant wave height. They have caused significant accidents and disappearing of ships worldwide.

Freak waves are caused by a superposition of multiple individual sinusoidal waves in the steady sea states that add up in a phase match so that their maximums briefly occur at the same time. As discussed in the article mentioned in section 2.6, the freak waves can also occur from instability. That is, the sea states cannot always be assumed to be stationary. Sea states are actually not stationary in the short term, which is why the sea state is collected from data over a period of 30 minutes to 3 hours. In the short term, frequency shifts and instability in waves may lead to energy compiling briefly into a freak wave. The rate of occurrence of freak waves is disputed. It was believed to be a rare phenomenon, but eyewitness accounts from ships have led to the belief that they occur more frequently than previously thought.

In the paper “New solutions of the C.S.Y. equation reveal increases in freak wave occurrence” by Andrade and Stiassnie, the probability of freak wave occurrence in random sea states is discussed. They look at the probability of freak waves in previous research by Crawford, Saffman, and Yuen, and further develop the equations by studying instability in JONSWAP spectra. The results below show the probability of freak wave occurrences in different cases of sea states, compared to the traditional Rayleigh distribution assumed occurrence. The results show that the occurrence of freak waves are probably more frequent than previously researched. Considering instability in freak waves is an improvement to past simplified models, and the results seem more compatible with eyewitness account occurrence. As shown below, the occurrence of freak waves that are twice the significant height could be up to 10%, or in the case of 3 times the significant wave height, could be 0.01%.



Cases	$P(H > 2H_s)$		
	Early stage	**Late stage**	**Whole**
Case a	0.0039	0.0114	0.0101
Case b	0.0044	0.0131	0.0105
Case c	7.6086×10^{-4}	7.8717×10^{-4}	6.3854×10^{-4}
Case d	5.20157×10^{-4}	5.1415×10^{-4}	4.5188×10^{-4}
Rayleigh	2.8493×10^{-4}		
Cases	$P(H > 3H_s)$		
	Early stage	Late stage	Whole
case a	1.0964×10^{-4}	7.6016×10^{-4}	6.1436×10^{-4}
case b	1.9381×10^{-4}	0.0012	7.9539×10^{-4}
case c	8.8408×10^{-4}	9.54017×10^{-7}	5.94267×10^{-7}
case d	2.0648×10^{-7}	2.0668×10^{-7}	1.3675×10^{-7}
Rayleigh	1.1742×10^{-8}		

2.5 Book chapter

Chapter 2 of the book Principles of Naval Architecture (1989) by Edward V. Lewis discusses ocean waves, their origin and their spectral representation. The most common and relevant mechanism for wave generation is wind. There are two mechanisms for wind generated waves. First one is wave generation by pressure fluctuations on the surface and the second is shear force acting on free surface ie. Water/air surface. Usually, the pressure fluctuations on the surface cause ripples. Then the formed waves are enlarged by shear force and finally they interact forming longer waves.

The random nature of waves is caused by the fact that wind direction and speed change constantly. Therefore, the pressure that creates waves varies all the time which causes waves to be different from each other. Basically, because wind is a random phenomenon, so are the waves. Since wind speed and direction change over time, even in a short period, the generated waves become more and more different which causes the sea surface and sea waves to be more and more random as time progresses. Even though wave elevation is a random process, it can be considered stationary for a 0.5 – 3 hours time window.

Spectral representation is used to represent the random wave process. For a specific operational area, measurement is collected about wave height and period (sea state). This data is represented as probabilities, with certain distribution and statistical properties. For short periods of time (30 min to 3 hr), these statistical properties are considered constant (the process is stationary). For example, in northern North Atlantic, there is 6.5% probability of having waves with height between 1-2 meters and period of 8.5 seconds.

FFT is used to extract components that make up this kind of wave, each component contributing certain energy to the original wave. This is called wave spectrum, from which we can calculate average and extreme wave elevation. There are two idealized spectrums used: Pierson-Moskowitz for fully developed sea and JONSWAP for developing sea. They are basically attempts to describe the ocean wave spectra in special conditions (after wind with constant velocity has been blowing for a long time). These spectra are calculated for different wind speeds but it has become customary to associate them with certain sea states (wave height and period) rather than wind speed.

The y-axis of these spectra is not the amplitude of the component waves but rather the energy (or power) spectral density which describes how the energy (or power) of the original wave is distributed with frequency. The integral of these energies is equal to the total energy of the original wave. In general, the power density spectrum is useful because it shows the frequencies with high power, then we can avoid or aim at them depending on the application. This is especially useful when structural response is of main concern.

2.6 Reflections on Scientific Articles

Time–frequency analysis of the sea state with the Andrea freak wave by Cherneva and Guedes Soares.

In the article "Time-frequency analysis of the sea state with the Andrea freak wave" Cerneva and Guedes Soares look at the behavior of large waves at the Andrea station. In this paper, unlike in the simplified theory, considers that in short term time intervals, waves are not a stationary process. In the normal frequency domain analysis of sea states, some information about the energy distribution is missed in simplifying the state to be assumed as stationary. This paper investigates the theory of joining time and frequency domains to one function that describes wave energy.

The paper analyzes the sea state in terms of a Wigner time-frequency spectrum and Benjamin-Feir instability. This means practically that the sea state is represented by a time-frequency spectrum that includes the instability of waves and possibility of energy transfer between waves in a sea state. The conclusions show that the freak wave at the Andrea station had energy spread over a wide frequency interval, which aligns with previous research. The wave group has a constant local frequency and reaches maximum energy when the frequency equals the frequency of the normal stationary spectrum. The complex spectrum might result from wave components coming from different directions.

Overall, this study relates to our project because we must consider freak waves in analyzing motions of Frostisen. The occurrence of freak waves is important to predict. It is also important to consider the behavior of these abnormal waves and look at the ways that the wave spectrum assumptions may not model reality. The course notes mention the instability or energy transfer of waves as a possible cause of freak waves, and this article solidified that understanding. In the course notes, the main explanation for freak waves is a superposition of waves traveling at different speeds that accumulate into one giant wave.

Marine Environments and Its Impact on the Design of Ships and Marine Structures by Michael K. Ochi (1993) presents a summary of information about environmental aspects relevant to ship design. They state that the stochastic prediction approach is commonly used the design process, but a lack of input information in terms of accuracy is what inhibits this this approach. As mentioned in the lectures before, this lack of really accurate input is a challenge when designers are trying to evaluate the sea keeping properties of a ship they are designing. Frostisen is ice going vessel and challenges with similar nature are raised when evaluating the possible ice loads and propulsion power in ice.

The friction and roughness of sea surface causes turbulence and this effect decreases as elevation from sea surface increases. The height where this turbulence comes negligible is around 200 meters, so this turbulence and its stochastic spectrum must be taken into account when designing marine structures or vessels and evaluating the possible drag force turbulence is causing.

Hurricane winds and associated sea severity forms another phenomenon that should be understood. This phenomenon can be divided into two stages: the growing stage of hurricane and fully developed hurricane. Wave height in the hurricane growing stage is typically much less than in fully developed sea since the duration of stable windspeed is short. The sea only develops if the fully developed hurricane lasts for a long time and the growing rate is really slow, but the sea spectrum still is not similar with fully developed sea.

The wind loads of high-speed winds and wave spectra are taken into account when designing a ship to operate in areas where hurricanes occur. As the Frostisen is travelling trough North and South Atlantic few times a year, this is subject which needs to evaluated. It is known that the Atlantic Ocean develops multiple hurricanes usually between June and November.

In the paper Michael K. Ochi shows a few different approaches to wave spectrum. The first is Pierson-Moskowitz Spectrum equation which was developed in 1964 based on approximately 70 fully developed sea spectrum. In this approach the wind speed affecting wave height is defined at a height of 19,5m. Other approach that this paper shows is a spectral formulation by Bretschnider in 1959 which can be used to represent sea spectrum to both fully and partially developed sea.

The statistical properties of wave heights provided by approaches discusser earlier provides valuable information considering the designing of ships, but also the statistical distribution of the wave heights is important. This is why these methods have been developed by multiple researchers and there are different approaches available. Longuet-Higgins approach which is relatively straightforward and does not require as much computational power like approaches developed by Lindgren in 1972 or Lindgren & Rychlik in 1982. While the approach is much simpler that the two previous ones, it still joints wave height and period with satisfactory accuracy.

Assignment 3

3.1 Equations of Motion

The general form of Newton's 2nd law states that the total force acting on a body as a function of motion (x) includes three terms:

- Mass (m)
- Damping (c)
- Stiffness (k)

$$F(t) \; = \; m\ddot{x} + c\dot{x} + kx$$

The above equation is formed, and it expresses the response of the system when we have free vibration. It also expresses the excitation and affects the frequency response function.

Considering ship motions, Newton's 2nd law can be redefined to correspond to the mass and added mass of the fluid moving with the hull (M & A). In that case, the equation takes into consideration also the damping factor (N) and restoring forces (S), which are related to stiffness in the general form of the equation. The added mass represents the amount of fluid accelerated by the object, and in this case by the ship. Now, the following equation is obtained:

$$[-\omega\hat{}2\ (M + A) + i\omega_e N + S]\hat{\vec{u}} = \hat{\vec{F}}_e$$

Overall, there is a 6 degrees of freedom motion system regarding ship motions, and those are: surge, sway, heave, roll, pitch and yaw. Considering Frostisen and the fact that it is a luxurious passenger ship, rolling, pitching and heaving of the ship are especially critical directions in terms of passenger comfort during the journey. Heaving is the linear motion along the vertical Z-axis, rolling and pitching on the other hand refer to rotation around longitudinal and transverse axis respectively.

Frostisen is supposed to travel through several smaller ports at least in the Arctic region and therefore there will be lots of maneuvering. The efficient maneuvering capabilities of the vessel are achieved certain equipment that enables applying moments that cause ship to yaw. Frostisen is consequently equipped with WTT's transverse bow thruster and Azipod propulsion system. Overall, the minimization of uncomfortable motions is essential part of operation of Frostisen.

When it comes to mass terms of the equation, the mass of the hull is continually improved along the design phases in the design spiral. At the same time, the vertical center of gravity (CoG) is taken into consideration as it is crucial factor. The harmonic motion components are greatly related to CoG. The added mass is much more difficult to estimate, and in most cases hydrodynamic simulations are needed to evaluate it comprehensively. Alternative to simulation of fluid around the hull is to utilize existing knowledge on similar hull forms.

The damping term is related to viscous forces of the fluid along the hull. Viscous forces are depended on the direction of motion of the fluid. The damping effect is caused by the friction between hull and water.

Especially, hull appendices cause damping. In case of Frostisen, the vessel is equipped with fin stabilizers that help ship to maneuver in rougher seas. Also, Azipods provide damping as they induce waves to the water surrounding the hull. The motion of the fluid is affected by this equipment and, consequently they have influence on the damping component of the equation of motions.

The restoring forces especially when ship is in roll or pitch motion, are related to metacentric height of the ship. The restoring moment for example, in roll motion, is depended on the transversal metacentric height. On the other hand, metacentric height is depended on center of gravity and geometry of the waterplane area. Hull of the Frostisen is rather slender but the vertical center of gravity (KG) stays in appropriate range mostly due to composite superstructure.

3.2 Influence of General Arrangement, Hull form and Operational Profile on EOM

The hull form affects the equations of motion in that the form of the ship affects the way that its motion responds to waves. Firstly, the general particulars affect the ship's motions. Frostisen is a relatively small ship, so the motions will be important because small ships have larger motions in waves than large ships. Since Frostisen is a cruise ship, the seakeeping is especially important to the comfort and safety of passengers. There are 6 equations of motions for a ship—one for each degree of freedom, 3 rotations and 3 translations. The most important equations of motions are those that lead to a restorative force, namely the heave, pitch, and roll motions. Besides the general particulars, the ratios between length, beam, and draft also have an important role in the equations of motions. In this section, we will discuss the ways in which the hull form, general arrangement, and operational profile affect the equations of motion and which are the most impactful.

The heave motion is affected by the hull form by the waterplane area. Ships that have a large waterplane area for its displacement will experience heavy heave motions due to the restoring force. The restoring force causing heave motions to oscillate is caused by the difference in displacement and buoyancy. Frostisen is not a particularly "beamy" ship, as shown in the comparison below. This comparison was developed during Principles of Naval Architecture to compare Frostisen's principal dimensions to those of the reference ships, expedition cruise ships of comparable sizes. As shown, the beam to length ratio was right along the trend line of existing ships. Frostisen's beam is even on the lower end of the trend, so excessive heave motions are not expected.

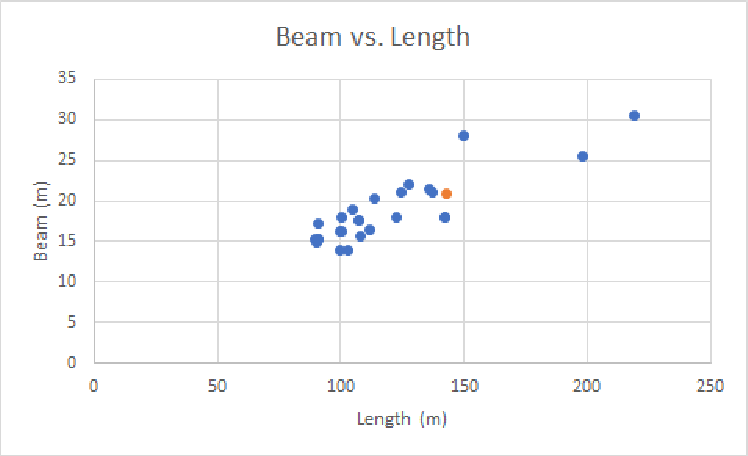


Figure 3.2-1: Beam to Length Comparison between Frostisen (orange) and Reference Ships (blue)

The metacentric height is one of the most important factors in seakeeping and stability. There is a balance between the two considerations as they have opposite needs. The stability of the ship is increased as the metacentric height increases, but the motions of the ship also increase as metacentric height increases. Therefore, at this stage in the design, the metacentric height must be checked to make sure that the motions are not excessive while not compromising stability. For our stability cases, the GM of intact stability cases ranged from 1.53 meters to 1.97 meters. The GM also depends heavily on the beam, so decreasing beam would also solve the problem of excessive motions.

The hull form affects the rotational motions in that the radii of gyration are dependent on the ship's geometry. The roll depends on beam, and the pitch and yaw depend on length. As mentioned previously, the roll and pitch are the most important of the rotational motions as they have s restoring force. The rotational motions are dependent on the radii of gyration and the distribution of weight. In this way, the hull form and general arrangement affect the rotational motions heavily. Besides the ship's geometry, the distribution of weight farther from the center of gravity causes large rotational motion.

In cruise ships, the vertical distribution of weight is important due to large superstructures. Frostisen has a composite superstructure to offset the weight of the ship, increase stability, and improve motions. The distribution of weight vertically and transversely affects roll motions, so the GA design should keep large weights near the center of gravity when possible. Roll motion problems should also be offset by fin stabilizers. The roll motion is the most important to passenger comfort and safety.

The operational profile affects the equations of motions in that the encounter frequency of the ship depends on the directions of waves compared to the ship's heading. The Drake Passage should contain the roughest seas for Frostisen's operational area, and also causes lots of beam seas. In the following section, the motions are calculated in NAPA for beam and head seas. The below diagram shows wave directions in the Drake Passage—as seen, the waves are perpendicular to the general ship path.

Additionally, wave criteria such as significant wave height and period are also inputs to the equations of motions and greatly affect the ship's motions.

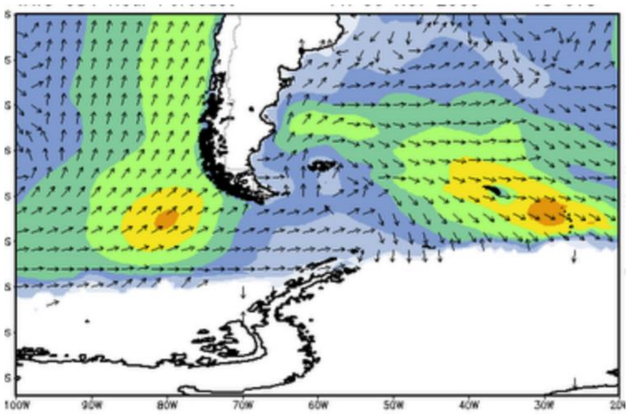


Figure 3.2-2: Wave Directions in the Drake Passage

3.3 Calculations using computational methods (NAPA)

Seakeeping software to be used in this course is NAPA. The team started getting familiar with the software for seakeeping and maneuvering calculations. There are two ways to study motions and loads in NAPA: macros and direct user interface. Macros are small codes that can be used in NAPA text editor to call existing functions and perform various operations with them. The direct user interface is a straightforward interface that allows choosing initial conditions and print results directly from an easy-to-use window. It was interesting for our team to start experimenting with macros first and perform more simple analyses for motions and loads. We will then move on to the direct user interface in the coming assignments to perform more comprehensive seakeeping analysis.

To experiment with macros, we analyzed bending moment and shear force for our ship in two sea conditions. The first is placing the ship in 1-m regular waves and the second is placing the ship in irregular waves with 1-m significant height. The input parameters used are:

- Loading condition: a loading condition was created and named "Transit", where fuel, fresh water, and grey water tanks are 50% full. Then ballast water tanks were filled to adjust the floating position to around zero trim. This corresponds to the case where the ship is sailing far in the open sea.
- Design speed: 17 kn.
- Heading angle: 90 and 180 degrees (beam and head seas). Beam seas are particularly important as they seem to be the prevailing seas in Drake Passage, which is the area with the roughest expected seas for Frostisen.

Figure and Figure below show vertical bending moment in 1-m regular waves and in irregular waves with 1-m significant height.

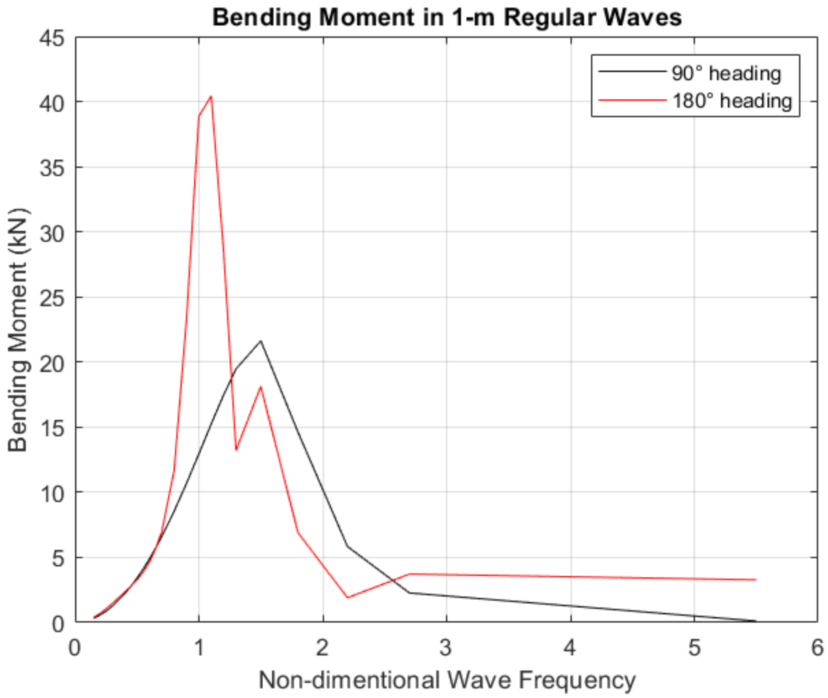


Figure 3.3-1: Bending moment caused by beam and head seas.

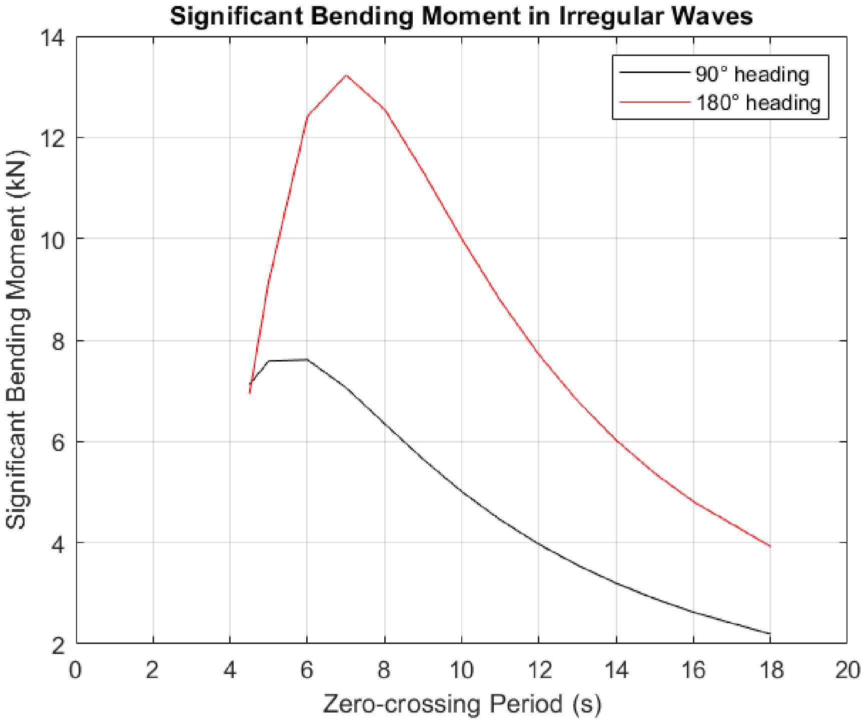


Figure 3.3-2: Bending moment caused by beam and head seas.

The first thing to note is that bending moment in head seas is significantly larger than that in beam seas. This is expected since bending is larger when bending a beam (the ship) longitudinally than when bending it transversally. The second thing is that bending moment in irregular waves with 1-m significant height is smaller than bending moment in 1-m regular waves. This is also expected since the mean wave height is smaller for these irregular waves.

Figure below shows shear force in 1-m regular waves. Shear force is also significantly higher in head seas than in beam seas. This is also expected if we consider the ship to be a beam subjected to longitudinal and transversal loads.

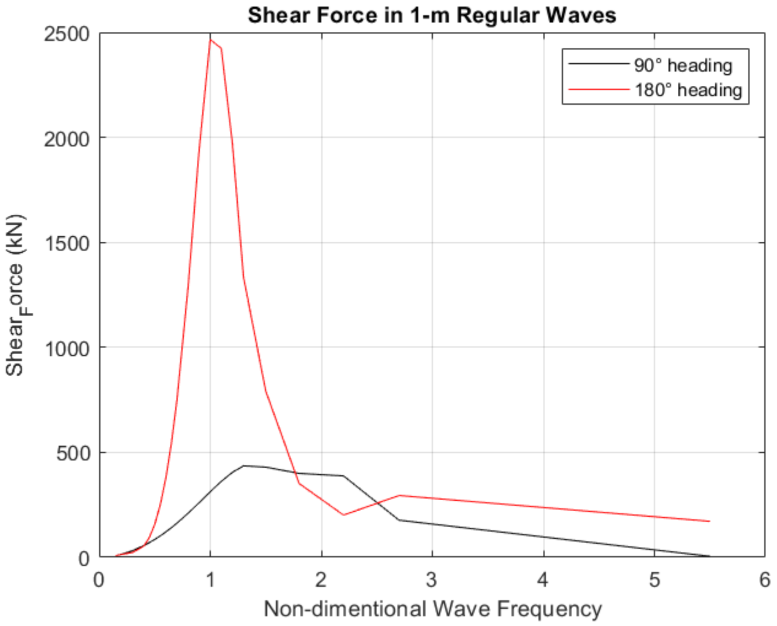


Figure 3.3-3: Shear force caused by beam and head seas.

Results of bending moment and shear force confirm that the software was used correctly to perform a seakeeping analysis. It's worth noting here that it was not possible to calculate shear force in irregular waves due to NAPA limitations. It was also not possible to change wave height from 1 m as this is the only calculation setup taught in the course Ship Design Portfolio.

The theory used in load calculations above is strip theory where the ship is sliced into 2D frames (strips) and calculations are done for each strip. In the next assignments, motions will be calculated using both strip theory and panel theory and hopefully a reasonable comparison can be drawn. The important motions to calculate are those with restoring force; namely roll, pitch and heave. Real sea states at Drake Passage will be used and motions will be compared against specific criteria (e.g., maximum allowed acceleration for passenger comfort). For the scope of this assignment, NAPA was successfully gotten familiar to.

3.4 Reflection on Scientific Articles

On the non-linearities of ship’s restoring and the Froude-Krylov wave load part by Jerzy Edward Matusiak.

Ship motions in waves can be evaluated with method called Laidyn (Matusiak, 2000b&2001) where the ship is considered as a rigid body. In this method there is a set of six equations of motion which take account projections of velocities of ships center of gravity, angular position of the ship and components of global reaction forces and moment vectors acting on the ship. Relation between projected velocities of the ship’s center of gravity and movement vectors can be calculated with matrix given by (Fossen, 1994 and Clayton & Bishop, 1982). They have also provided another matrix which can be used to solve relations between angular velocity vector and the Eulers angles which describe the ship’s angular position. These equations and relations of different components are solved numerically which I assume is because they are rather complex.

There are many approaches which take account the non-linear nature of restoring forces, Froude-Krylov forces and moments in waves. Froude-Krylov forces are forces that are generated by unsteady pressure field which is caused by undisturbed waves. These approaches can for example be extensions of static buoyancy curve-based models, Multivariable extensions of Taylor expansions or boundary element methods.

It is commonly believed that restoring forces, Froude-Krylov forces and moments are the most important contributors to non-linearities in forces that act on a ship’s hull. Evaluation of these can be done with discrete panel method, which takes account the ship’s position in coordinate system as well the pressure in each panel. There are 3 ways to evaluate the acting pressure in the panels, which will give slightly different results. These are: Linear Froude-Krylov, Faltinsen’s pressure profile and Stretched pressure profile.

In the paper a similar simulation data was used, and the ships motions were calculated with all of these 3 methods. The results differ a little bit, but the difference is not significant. It can't really be told which of these methods are most accurate or will give best results.

Quick Strip Theory Calculations in Ship Design by J.M.J. Journée

This paper argues that ship design is usually focused on still water performance and other desirable pieces of information are seakeeping properties as motions, accelerations, added resistance and bow slamming. This information can be estimated in the design phase with model test, but they are expensive and time consuming.

The paper shows calculation method based on strip theory which could be used for ship design purposes. What makes this method good and desirable, is its low demand of computational power and therefore short computational times. This method takes advantage of database which consists all information in two dimensional hydrodynamic coefficients for cross sections. This way all the hydrodynamic problems can be solved efficiently. According to strip theory, the total hydrodynamic coefficients for ship can be found by integrating the sectional values for over the ship's length.

The paper argues that the strip theory is based on slender hull forms, but it can still deliver effective predictions even for ships which have length to breadth ratio of 3. Another thing this paper points out, is that because the strip theory is based on potential flow theory, viscous effects are neglected. This can lead to huge problems when roll motions at resonance frequency. In practice the damping and other viscous effects are evaluated with empirical formulae. This is something we should keep in mind if we do any calculations of Frostisen's roll motions and the results look odd at frequencies where parametric roll appears. Also because the strip theory is based on linearity, the evaluated motions should be small relatively to the cross sectional dimensions.

As a result, this method will give accurate results for few exceptions: The ship's length to breadth ratio should be three or greater, the motions should be relatively small or the ships submerged part is relatively big (it has a large bulbous bow for example). This makes this method valid if we want to try on Frostisen. Frostisen's length to breadth ratio is over three and in not so severe developed seas the movements could be estimated with this method. For Drake's Passage where the most severe sea conditions are encountered, this method would probably give inaccurate results as the movements would not be small.

Assignment 4

4.1 Book chapter

Chapter 2 of the book Basic Ship Theory (2001) by Rawson, K.J. Tupper discusses seakeeping qualities and sea worthiness. Sea worthiness generally describes all the aspects that affects the ship's ability to fulfill its mission in all sea conditions. Ship's motions are huge part of sea worthiness and excessive motions hinder the ship's shea worthiness a lot. Excessive motions in passenger ships can cause a bad reputation reducing income the ship produces. In war ships too large movements can cause a need of really large stabilization systems for weaponry.

Wetness is situation when there is significant amount of water in the main deck. Solution to this problem is mainly increased freeboard height. For example, ice build-up can be lessened. Slamming in the other hand is action where the pressure in ship's hull becomes very large and causes sudden change in vertical acceleration which is followed by vibration of ship's girder in its natural frequencies.

Pitching, heaving and roll is caused by turning motion or waves. Pitching causes larger vertical movements at both ends of the ship, which is why typically passenger ships have most of the accommodation spaces in two thirds from the middle of the ship to aft or bow. Roll motion of ship produces larger camber than pitching and the largest angles usually happen when the ship is in parametric roll motion. Roll and pitch are oscillatory motions which could be dampened if necessary.

Surging is the ship's sped variation which is caused by waves. The effect usually is not so huge that it would be really noticeable by passengers or crew. A ship with length of 146m will have a surge effect of about 0,25 knots in 5m waves. Sway is movement where the waves cause ship to drift sideways. If the transverse force affects more on other end of the ship, at the same as sway occurs, yaw is happening too. It means that the direction of the ship is changed because of the external force caused by waves.

4.2 Seakeeping Analysis Simplifications

The seakeeping analysis of ships can be done by utilizing NAPA-software. As previously discussed, NAPA is used during the course for seakeeping and maneuvering calculations. NAPA is a comprehensive tool that can be used to calculate response in regular and irregular waves, seakeeping criteria, limiting significant wave heights, number of failures per hour and downtime. The basic idea behind NAPA-calculations is that it utilizes the data of created ship, for example, hull form and weights. The variables used in the calculations are discussed more in detail in the specific calculation chapters.

4.3 Response Amplitude Operators

The response amplitude operators (RAOs) are transfer functions that make the response meaningful. The particular solution of the equations of motion of the ship assumed as a rigid body in linear waves is given as a function of the input frequency. The seakeeping analysis is generally done in the frequency domain, where the input sea states are given in energy as a function of frequency. The resulting motions are then calculated in the frequency domain where a transfer function is needed to transform the solution of the equations of motion into the frequency domain. The following equation shows how linear theory can multiply a sea spectrum as a function of frequency by the square of the RAO to get the response spectral density, where Sr is spectral density, and S is sea spectrum.

$$S_r(\omega_e) = \left|H(\omega_e)\right|^2 S(\omega_e) = RAO^2 S(\omega_e).$$

The following figures show the RAOs for the 1.9 meter and 6 zero crossing period sea state input case, for the input speeds of 10 knots. The other cases are shown in the appendix. Each case is calculated at headings of 0, 45, 90, 135, and 180 degrees. The results are logical. The response function is given as a nondimensional amplitude of motion plotted against square root of ship length to wavelength ratio.

For the heave case, in the case that the response exceeds 1, the wavelength is larger than the ship length, going below just after the ship length exceeds wavelength by 2. In the other headings, the motion response peaks slightly at around 1.5 (ship length is around twice as long as wavelength). The sway function is also maximum in 90 degree heading. This of course makes sense as the sway motion is maximized by force in that direction. This occurs just after the ship length exceeds twice the wavelength. As expected, the sway, heave, and pitch motions are low after the ship length exceeds wavelength. The roll motion has resonant behavior. The maximum motion occurs when the ship length is around 3 times larger than the wavelength. Again, logically, the maximum occurs at 90 degree heading. In the yaw case, as expected, the maximum occurs when the ship length is equal to the wavelength.

Surge motion is unable to be calculated using strip theory, as the surge forces are much smaller than the others under the slender body assumption.

At 10 knots:

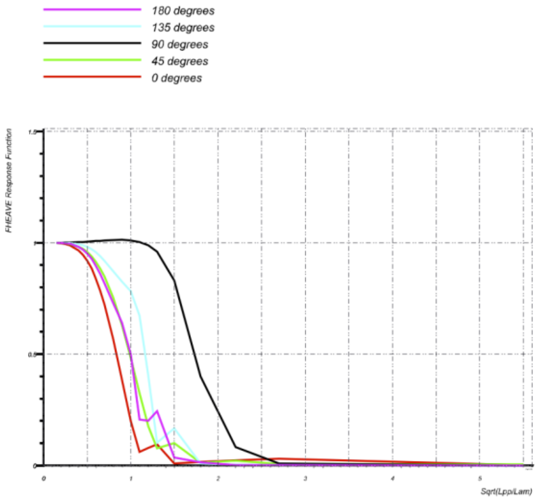
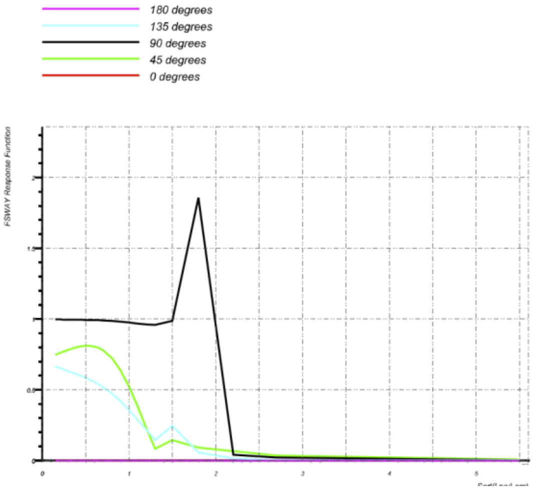


Figure 4: Heave RAO 10 knots



Sway RAO 10 knots

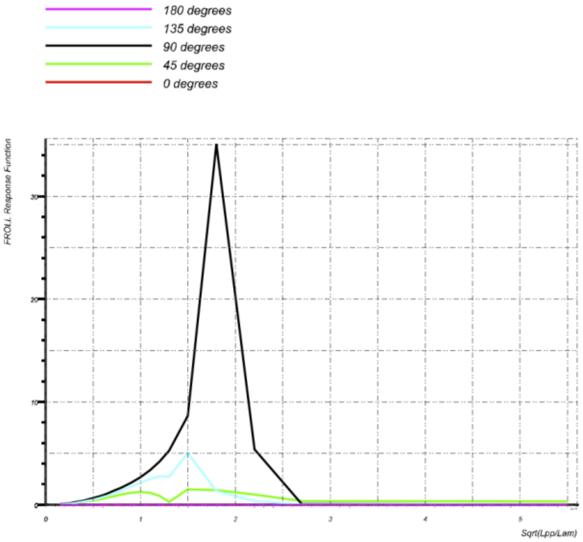
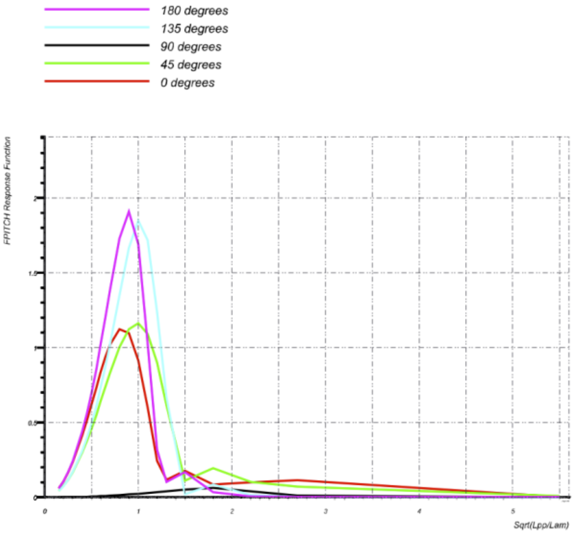


Figure 5: Roll RAO 10 knots



Pitch RAO 10 knots

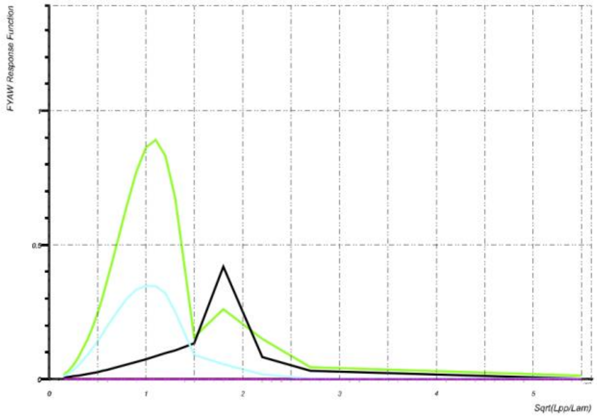


Figure 6: Yaw RAO 10 knots

4.4 Global Loads and Motions

4.4.1 Global Loads

As discussed in assignment 3, bending moment and shear force were calculated in NAPA for regular and irregular waves. For full details, see section *3.3 Calculations using computational methods (NAPA).*

4.4.2 Motions

Ship motions were calculated for 4 speeds and 4 sea states with predictions of 3 hours maximum. Ship speeds analyzed are zero, 10, 15, and 18 knots. These values correspond to service and design speeds of Frostisen. Table 6 below shows significant wave heights, zero-crossing periods, and the corresponding Beaufort scale for the sea states analyzed.

Sea state	Beaufort Scale	Significant Wave Height (m)	Zero-crossing Period (s)
4	5	1.9	6
5	6	3.3	7
6	7	5	9
7	8	7.5	10

Table 6: Motions were tested for sea states 4 to 7.

Speed (knots)
0
5
10
18

Table 7: Ship speeds used in calculations.

The highest probable sea state in which the ship is going to operate is sea state 4. In our research into the suitability of our chosen sea states, we found that sea states 6 and 7 are extreme cases which we will avoid in operation. The paper "Small scale open ocean currents have large effects on ocean wave heights" (Ardhuin, 2016), discussed in Section 2, concludes from their research that the 99th percentile of significant wave height distribution in the Drake Passage is 6.59 meters. The 96th percentile was found to be 6.4 meters, which means that sea state 5 is fairly unlikely to occur and sea states 6 and 7 are very unlikely to occur. Our ship can reschedule itineraries as needed but doesn't expect to encounter unsafe conditions regularly.

The calculations were done for the six degrees of freedom: roll, pitch, heave, yaw, sway and surge. The whole set of calculations was run twice: first using strip theory then using panel method. Results of the two methods of calculations were then compared. Table 8 below shows maximum values for the six degrees of freedom when all speeds and all sea states are considered. It also shows the conditions under which this maximum value occurs.

Motion	**Strip Theory**	**Panel Method**
Roll	18.5° (10 knots, sea state 7)	24° (10 knots, sea state 7)
Pitch	≈5.5° (all speeds above 10 knots, sea state 7)	≈5.2° (all speeds above 10 knots, sea state 7)
Heave	3.7 m (all speeds, sea state 7)	3.8 m (zero knots, sea state 7) Heave clearly decreases with increasing speed.
Sway	3.9 m (10 knots, sea state 7) **Speeds above 10 knots were not tested**	3.7 m (10 knots, sea state 7) **Speeds above 10 knots were not tested**
Yaw	2.3° (10 knots, sea state 7) **Speeds above 10 knots were not tested**	1.5° (10 knots, sea state 7) **Speeds above 10 knots were not tested**
Surge	Strip Theory in NAPA unable to calculate surge	4 m (10 knots, sea state 7) **Speeds above 10 knots were not tested**

Table 8: Maximum motion when all speeds and all sea states are considered.

Strip theory suggests that maximum roll angle happens at 10 knots and sea state 7 and it's equal to 18.5°. Panel method; on the other hand, suggests that maximum roll angle is 24°. This is a large difference and we believe panel method result is closer to reality.

At the highest probable sea state (sea state 4), the maximum roll angle is 11° (strip theory) or 15° (panel method). This maximum roll angle happens at 10 knots. The captain has two options to reduce this roll angle; either activate fin stabilizers or increase ship speed beyond 10 knots.

In contrast to strip theory, panel method shows a clear decrease in heave motion with increasing speed. This makes sense as when ship speed increases, the ship "spends" less time in wave troughs and crests and therefore heave motion is less.

It's worth noting here that calculating yaw, surge and sway motions in NAPA for high ship speeds (above 10 knots) was problematic and didn't produce meaningful results. For example, sway motion calculated was around 1000 meter for ship speed of 18 knots. Strip theory is also unable to calculate surge motion.

Overall, the results presented in Table 8 above seem reasonable and expected. The sections below give detailed results for ship motions at all sea states and all ship speeds using strip theory and panel method.s

Strip Theory

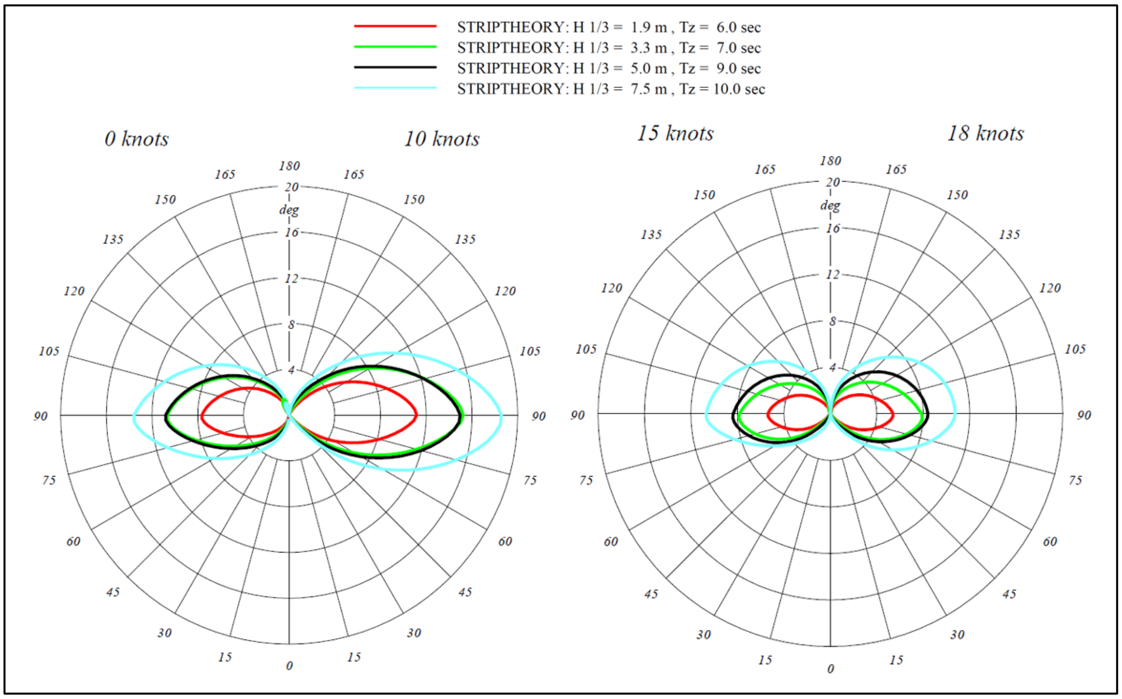


Figure 4.4-1: Roll motion under different speeds and sea states (Strip Theory)

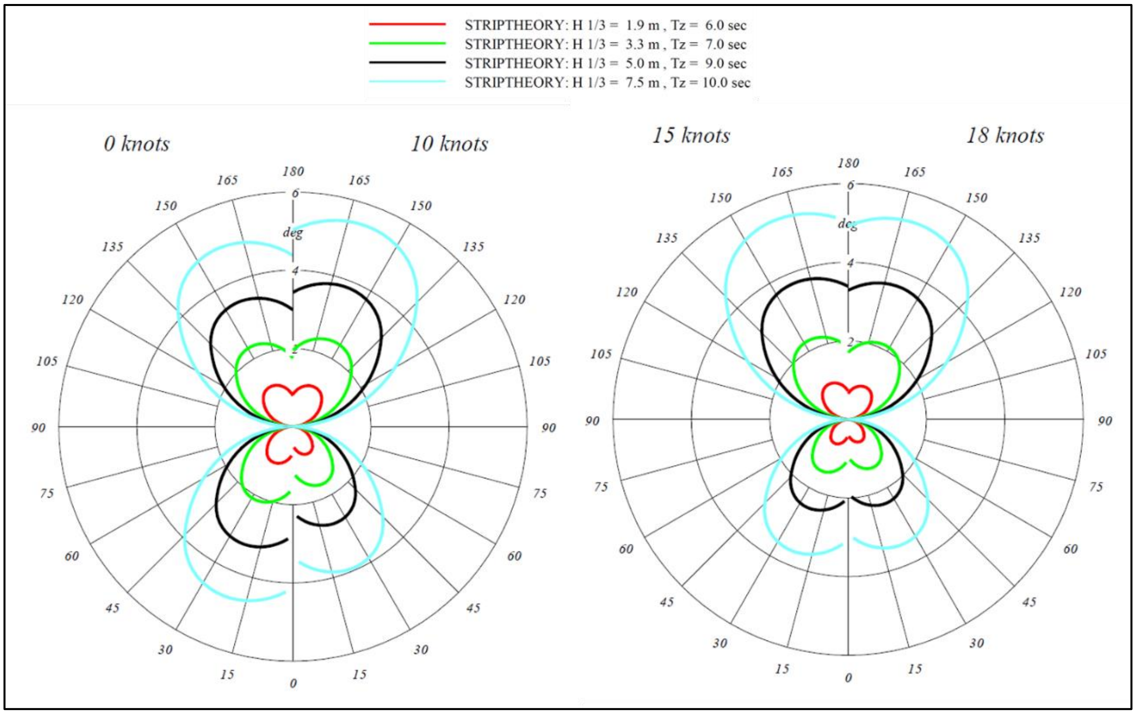


Figure 4.4-2: Pitch motion under different speeds and sea states (Strip Theory)

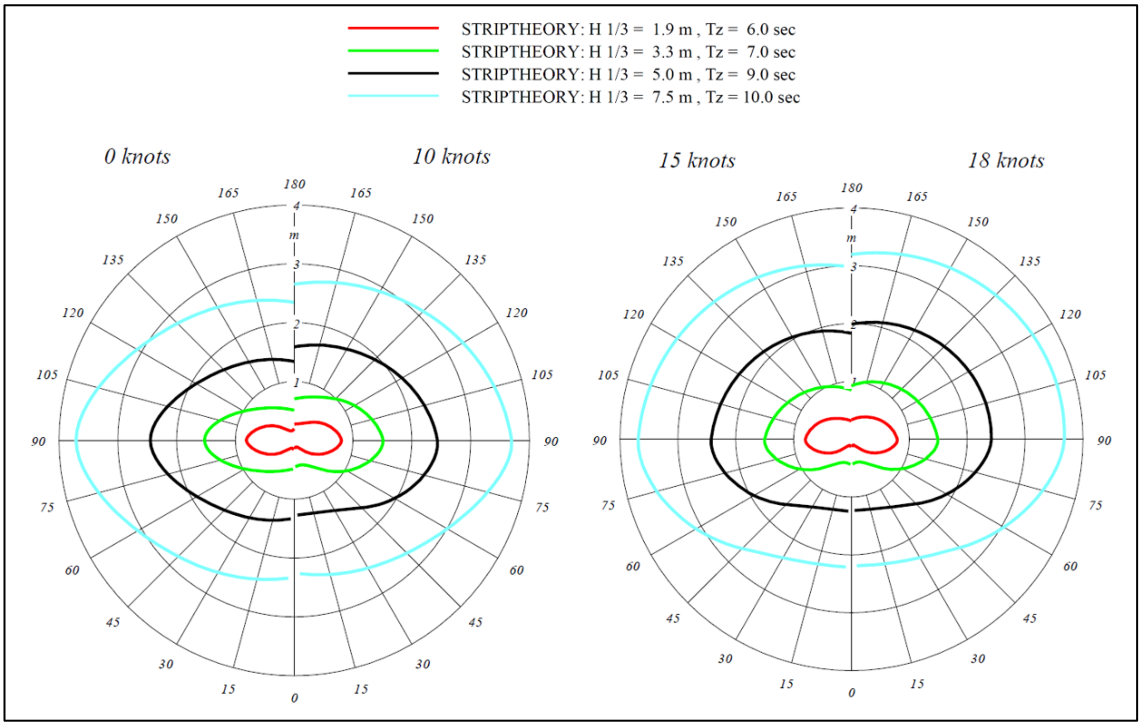


Figure 4.4-3: Heave motion under different speeds and sea states (Strip Theory)

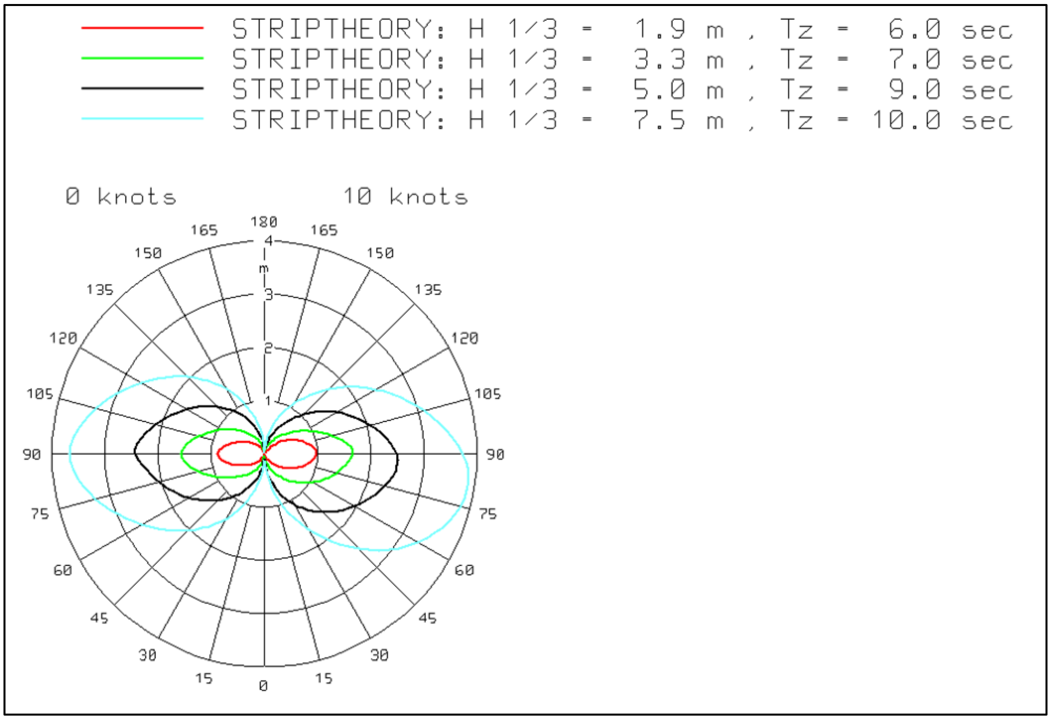


Figure 4.4-4: Sway motion under different speeds and sea states (Strip Theory)

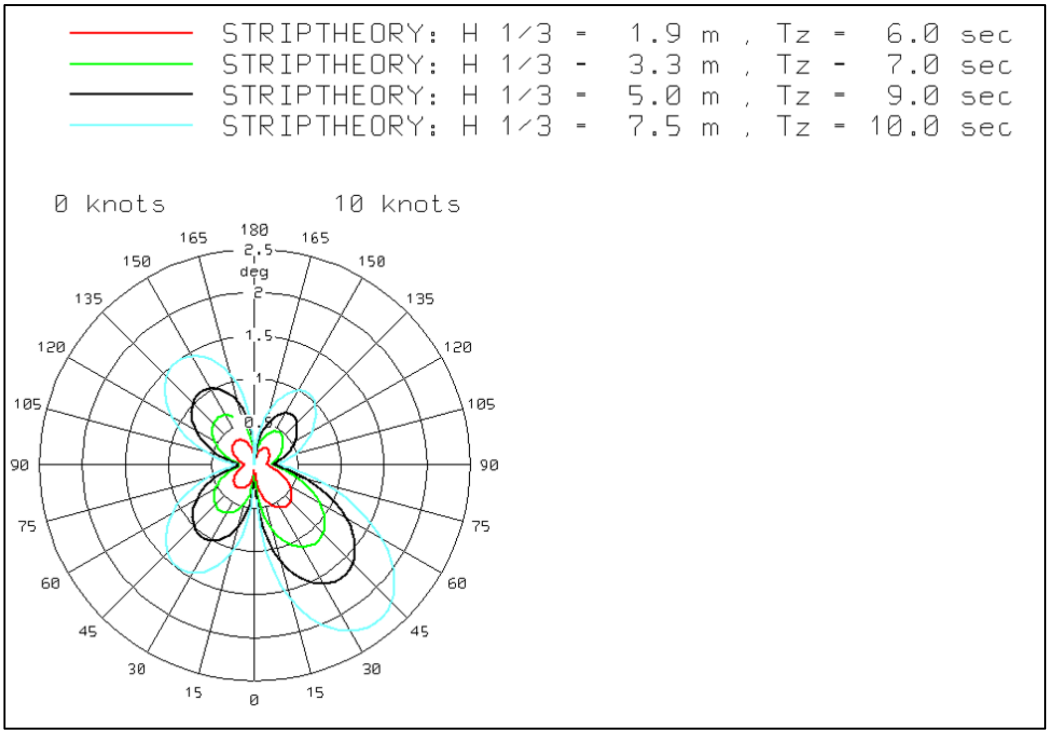


Figure 4.4-5: Yaw motion under different speeds and sea states (Strip Theory)

Panel Method

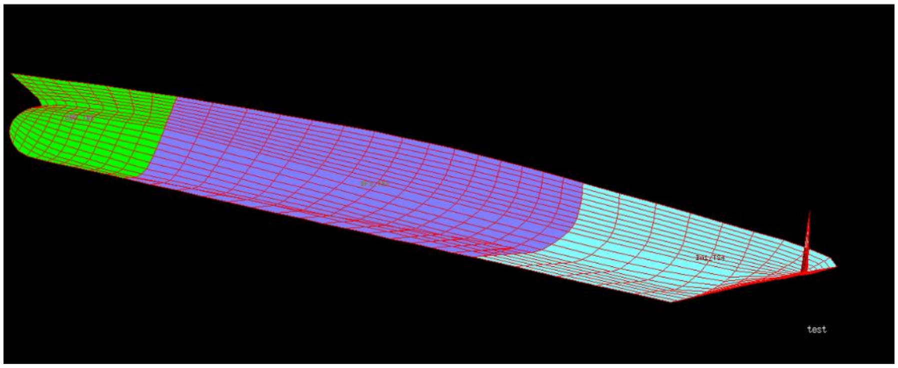


Figure 4.4-6: The mesh consists of 700 panels made in NAPA.

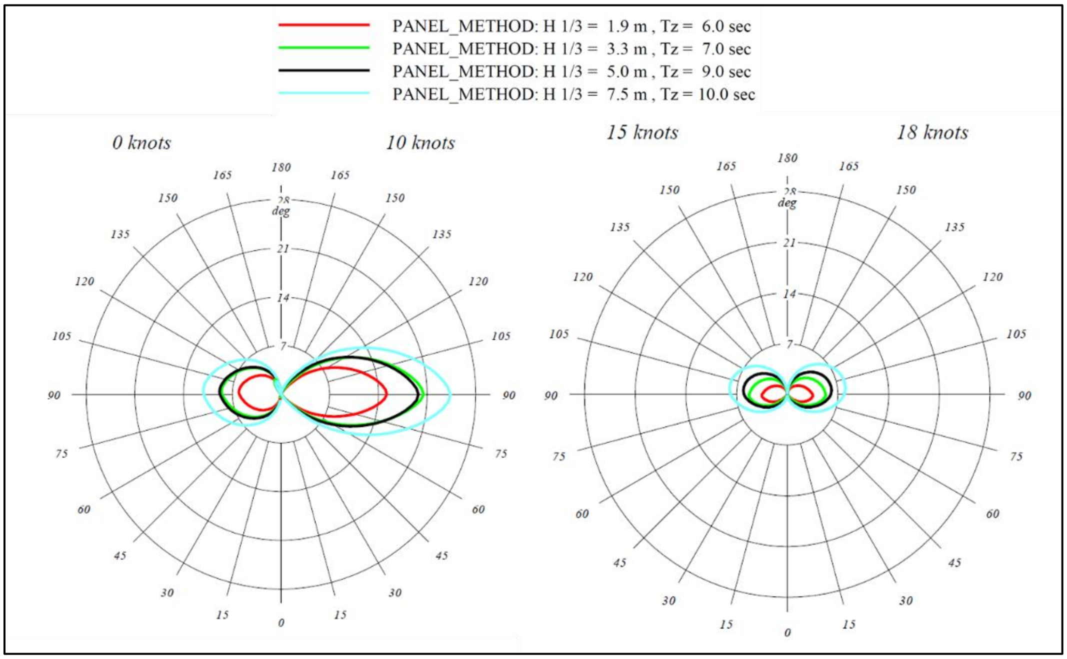


Figure 4.4-7: Roll motion under different speeds and sea states (Panel Method)

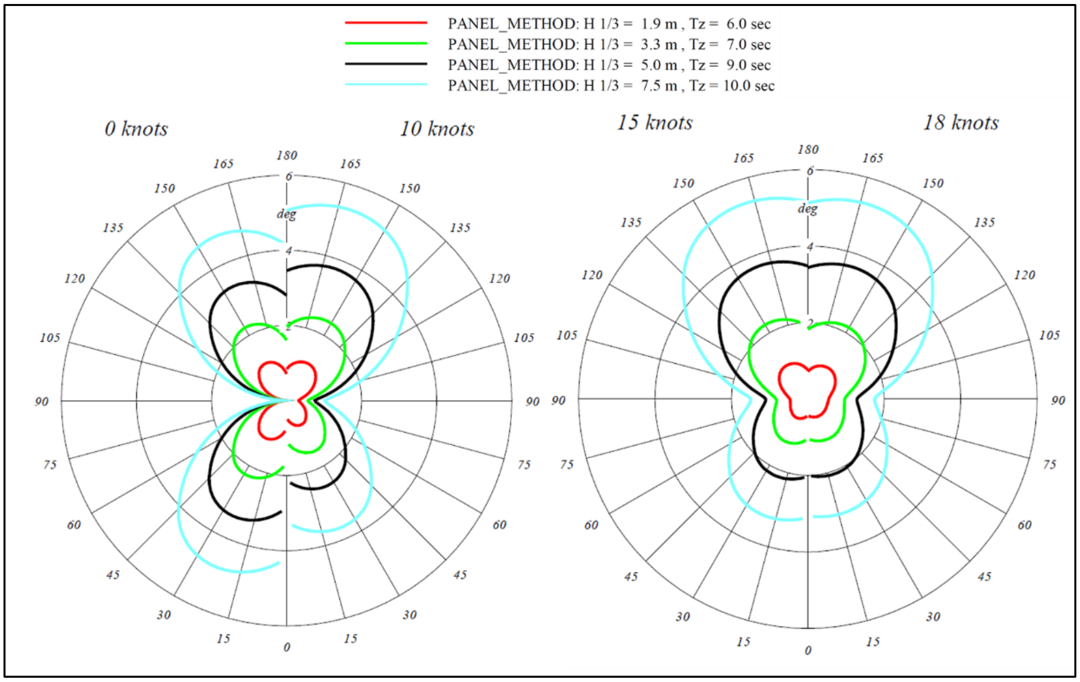


Figure 4.4-8: Pitch motion under different speeds and sea states (Panel Method)

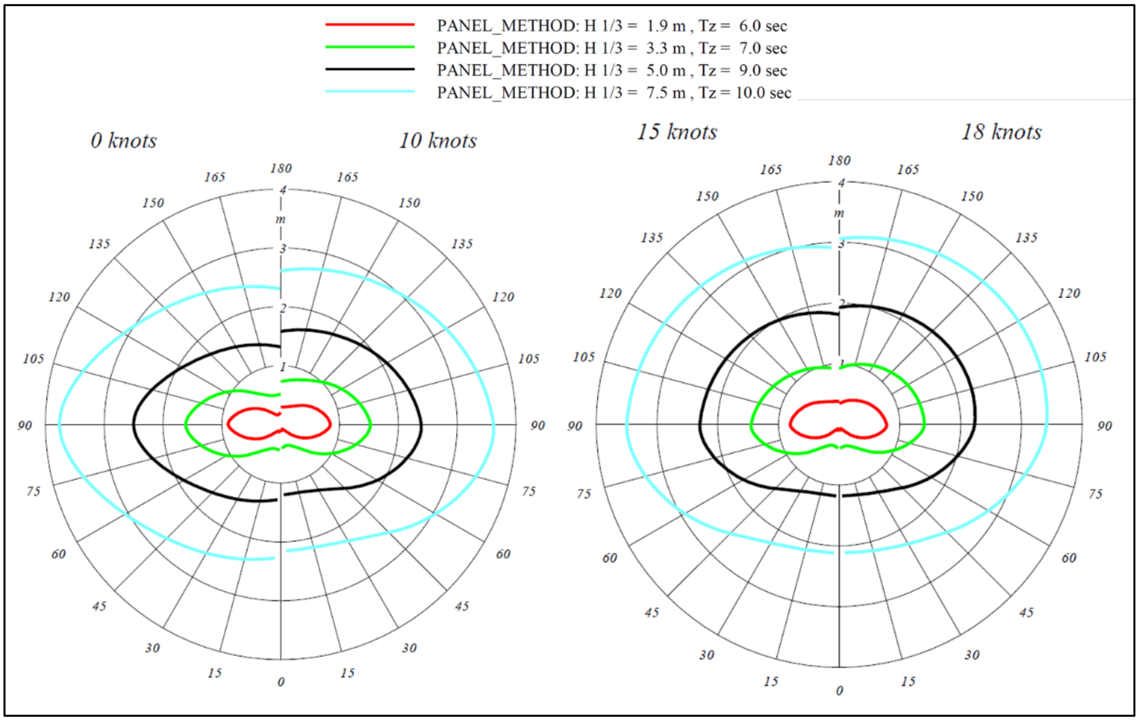


Figure 4.4-9: Heave motion under different speeds and sea states (Panel Method)

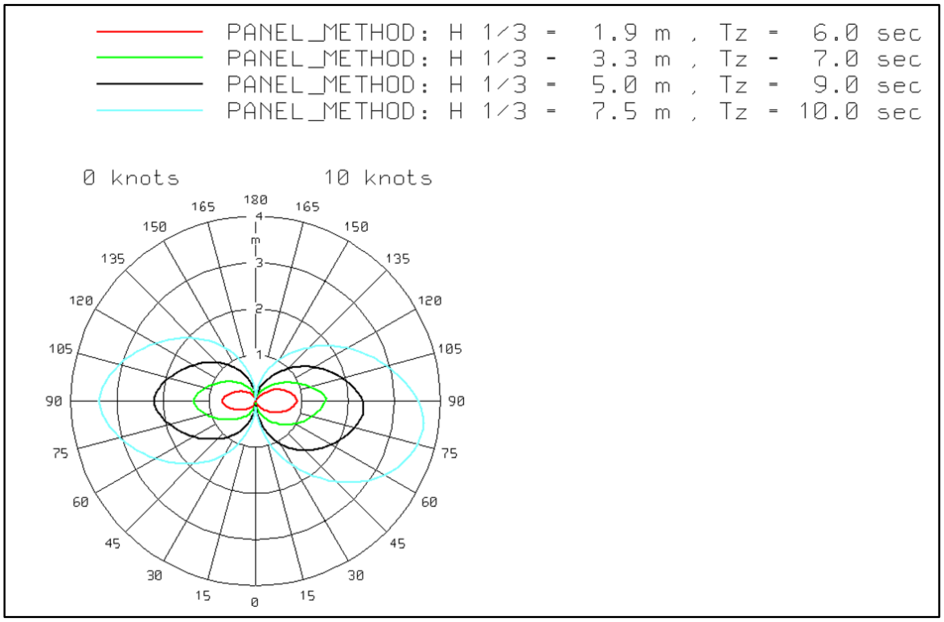


Figure 4.4-10: Sway motion under different speeds and sea states (Panel Method)

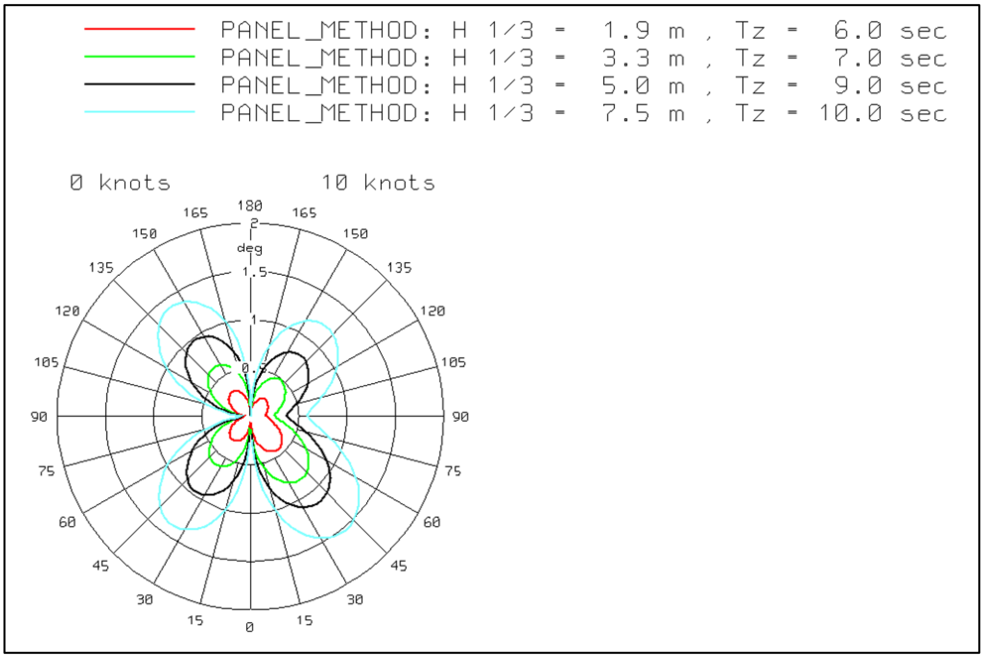


Figure 4.4-11: Yaw motion under different speeds and sea states (Panel Method)

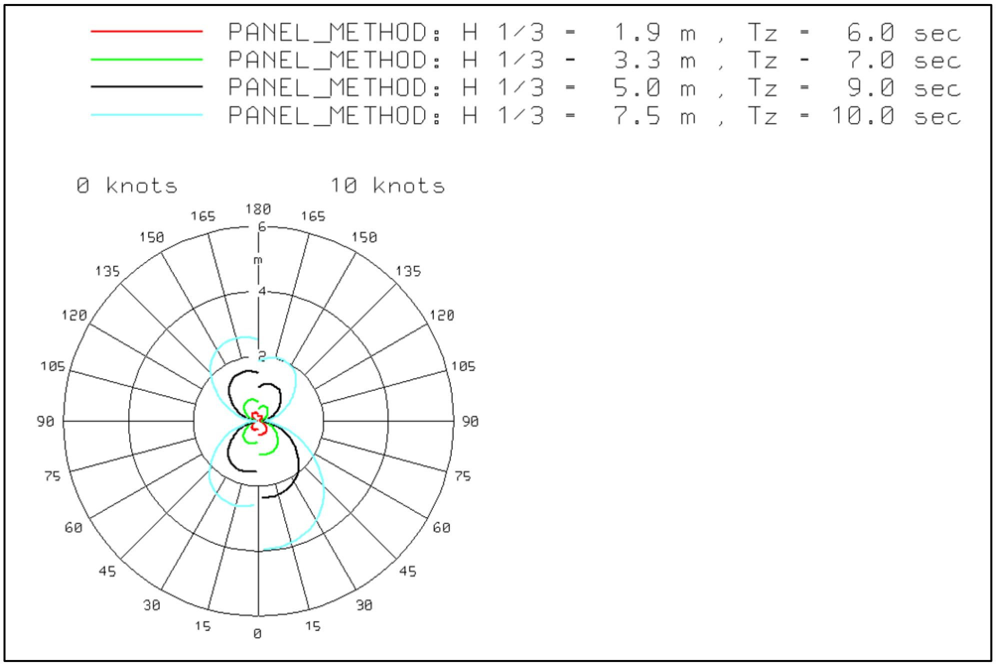


Figure 4.4-12: Surge motion under different speeds and sea states (Panel Method)

4.5 Accuracy of Results

There were few minor question marks in the results we got. In sea state 4, the maximum roll angle according to strip theory is 11 degrees, but panel method gives 15 degrees. As mentioned in the lecture 7, if the motions are excessive the strip theory-based method will have error in the results because the of the non-linearities. The panel methods suit better for larger movements. This may be one reason the results have difference between them. Hsiung (1991) mentions that strip theory may give better results of pitch motions in long waves. If the scenario is about whole range of wave frequencies and Froude number is high, panel method will provide better accuracy. He also states that for overall evaluation, the panel method is better than strip theory-based method, especially for fuller hull shapes. This indicates that in these situations where the results differ, we should lean more towards the panel method.

Both strip and panel methods are presented for solving the linear hydrodynamics problem. To simplify, strip method is rather simpler of these two, mainly because it is two dimensional.

Generally, it is well understood that the strip theory is based on many assumptions. It needs to be realized that there are many non-linear factors such as three-dimensional effect, advance speed effect, viscosity effect and section-shape effect that have their influence on the results. Nevertheless, strip method is overall very useful tool as it provides sufficient accuracy in most cases. The most notable part of utilizing strip methods is that the computing time is far less than with other methods. Consequently, it can be concluded that strip method is cost-efficient solution to many purposes.

Assignment 5

5.1 Book Chapters

Basic Ship Theory (5th Edition), Chapter 12 – "limiting seakeeping criteria"

The Ships ability to carry out its mission safely and efficiently is crucial and it can be evaluated with limiting seakeeping criteria. These limits can be set by some of the ship's systems, ship itself (structures for example) or comfort of crew or passengers. There are guidelines and standard values for different criteria which are often used in preliminary design phase but these should not be blindly thrusted. The new design may have some features that need different acceptance levels for some criteria and each should be evaluated as design progresses. According to the book chapter, most frequently used criteria are speed and power in waves, slamming, wetness, propeller emergence and impairment of human performance.

Speed and power in waves are mainly determined by the severity of sea state and the power needed to drive the ship at certain speed increases compared to calm sea state. Waves are causing increased resistance and the propulsion efficiency decreases due to changed environment where the propeller operates. typically ships that have low displacement to length ratio and very fine hull form will maintain higher speed in severe sea state, but Frostisen's hull is not really fine, so this will influence our ships operating speed when sea state develops severe. However, this is not only a bad case. With lower speed in waves slamming decreases and the risk of damage drops also. Wetness reduces as well.

Principles of Naval Architecture (Second Revision), Volume III - Motions in Waves and Controllability, Chapter 5 – "added resistance"

As described before, the power demand increases when ship encounters severe sea. This phenomenon is called added resistance and it is caused by direct wind and wave action, indirect effect of waves associated with ship motions and rudder action. Direct wind and wave action add resistance through hydrodynamic drag effect and the amount of added resistance due to these can be decreased with bow and superstructure design. In Frostisen's case, the bow and superstructure are designed with this factor in mind and the added resistance due these factors are minimized. According to the book chapter rolling of the ship presumably increases resistance and the effect is greater if bilge keels are fitter into the ship. As Frostisen is too stable ship, rolling damping system is needed to reduce excessive accelerations on board and therefore this factor will add resistance in severe sea. Internal Anti-rolling system could reduce the added resistance as those does not create any additional drag.

Basic Ship Theory (5th Edition), chapter 13 – “Assessment of manoeuvrability”

Maneuverability of a ship is can be evaluated with zig-zag maneuver, turning circle, spiral maneuver and pull-out maneuver. While these tests are performed, drift angle, advance, transfer, tactical diameter, diameter of steady turning circle, pivoting point, loss of speed when turning and heeling angle can be measured.

Tactical diameter is diameter of a half-circle which the ship travels when its heading is changed 180 degrees. typically, tactical diameter to length ratio is around 4,5 for merchant ships and anything over 7 is considered very poor handling.

5.2 Simplifications of the Model

To perform seakeeping, maneuvering, and added resistance computations, we used NAPA. For the seakeeping model, linear theory is assumed. The theory for the model includes an assumption of low speed. As our results were a bit weird at higher speeds, this assumption might have been invalid for our case above 10 knots. Other assumptions include deep water assumption, which is valid in our case, and an assumption that the hull does not affect the waves. Free surface effect is also not accounted for.

For the maneuvering and added resistance model, the viscous damping is ignored which allows potential theory to be used. Waves are also assumed to be linear. Another simplification is that ice is not considered. Frostisen will encounter some ice as the operational area includes arctic and Antarctic regions. The wave theory is based on linear waves and ice flow is not a factor. The assumption that the waves are linear, that the hull does not affect waves, and that ice is not accounted for in the model all add uncertainty to our results. The assumptions theoretically do not make a big difference, but many small simplifications can add up to inaccurate results.

NAPA’s maneuvering manager is based on traditional propulsion with a rudder. Frostisen does not have a rudder and uses Azipods as the main propulsion. The NAPA maneuvering model includes a macro for Azipods which was provided in the Ship Design Portfolio workshop. In this simplification, the rudder is still modeled but made very small. The Azipod model is not entirely accurate to the design and the results may be affected.

5.3 Seakeeping Criteria and discussion of results

Two seakeeping criteria were assessed: seasickness and roll angle limit.

Motion sickness incidence (MSI) was calculated in the most fore location of the ship which typically experiences higher accelerations than other parts of the ship. MSI is normally less than 10% for passenger ships (Colwel, 1994) so the criteria limit was set at 10%. The calculation was done for sea state 4 with significant wave height of 1.9 m.

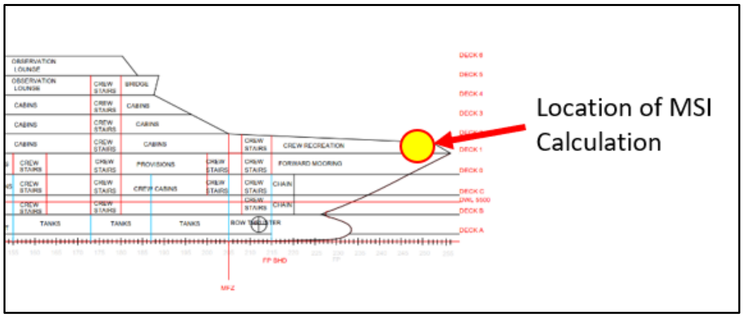


Figure 5.3-1: Motion sickness incidence (MSI) was calculated in the most fore location of the ship.

Figure and Figure below show number of times MSI limit is exceeded per hour when sailing at 15 knots in beam and head seas. In beam seas which are prevalent in Drake Passage, MSI limit is exceeded about 2 times per hour, which is acceptable. In head seas, MSI limit is exceeded around 12 times per hour, much higher than in beam seas. This is expected as seasickness is thought to be linked to heave accelerations which are higher in head seas than in beam seas.

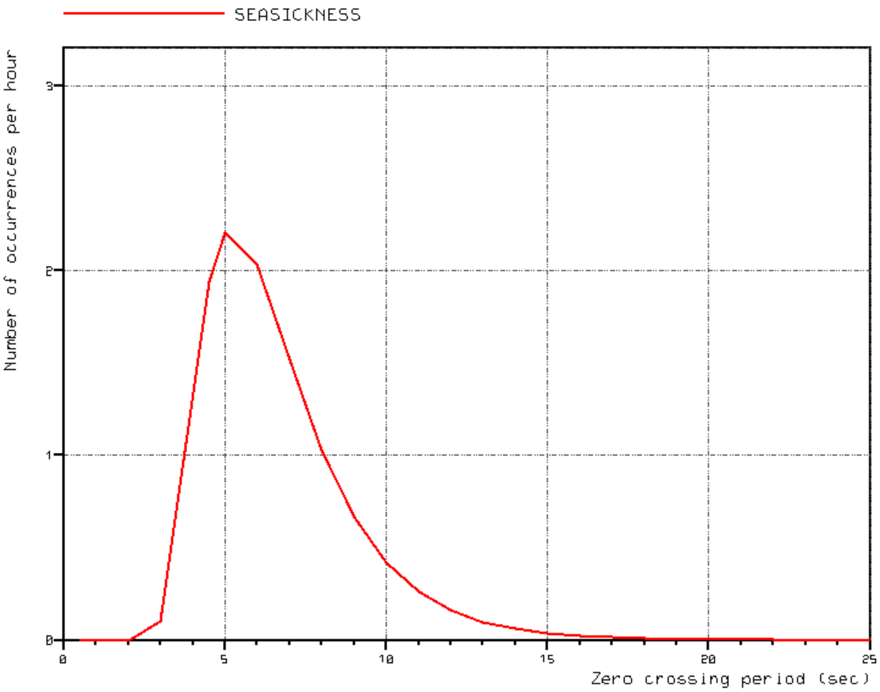


Figure 5.3-2: Number of times MSI limit is exceeded per hour at 15 knots and beam seas (prevalent in Drake Passage).

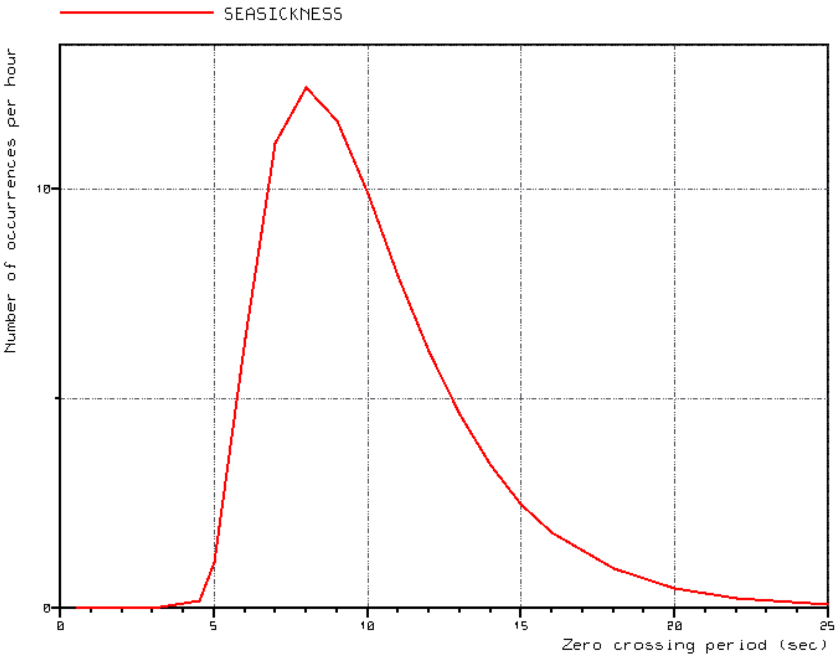


Figure 5.3-3: Number of times MSI limit is exceeded per hour at 15 knots and head seas.

The second seakeeping criteria assessed is roll angle limit. The limit was set at 10 degrees and calculation was done in sea state 4 (significant wave height = 1.9 m). As seen in Figure , roll angle exceeds 10^o around 15 times per hour when the speed is 15 knots and the ship is in beam seas. This supports our initial prediction that the ship will need roll reduction devices and the choice was made to install fin stabilizers as discussed in assignment 1.

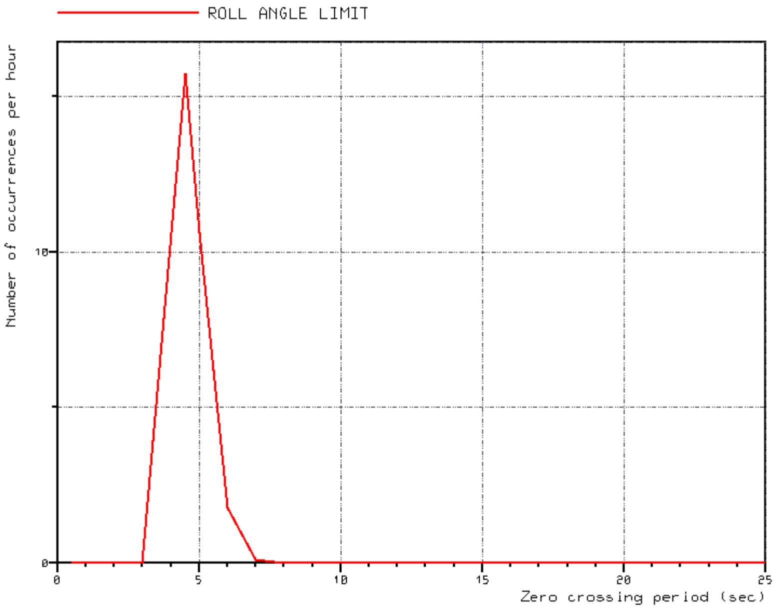


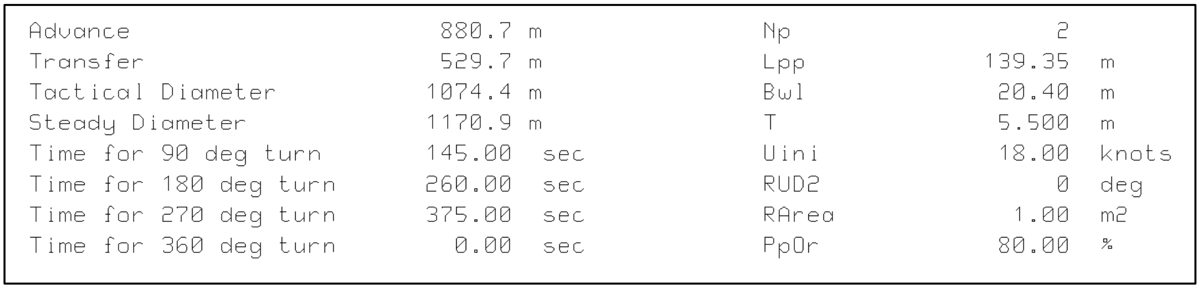
Figure 5.3-4: Number of times per hour roll angle exceeds 10^o (15 knots, beam seas).

5.4 Maneuvering and Added Resistance

5.4.1 Maneuvering

Maneuvering can be simulated in NAPA Seakeeping Manager for ships with conventional propulsion. For ships with azimuth propulsion like Frostisen, maneuvering simulation is more challenging. NAPA macro needs to be used to simulate maneuvering in this case. The macro was used to simulate turning circle and zig-zag tests, where the input was ship geometry and particulars with 2 azimuth propulsors. Turning circle and zig-zag tests were specifically chosen for the simulation to investigate Frostisen's ability to maneuver in tight waterways around the coast of Norway as well as busy harbors. Therefore, these tests relate to the operational profile and environment in which Frostisen will sail. All input parameters used in the simulations are specific to Frostisen.

Ship speed was tested from zero to 18 knots with 1 knot interval. Figure 5 and Figure 6 show input paraments and results of turning circle test at 18 knots.



```
Advance                        880.7 m              Np                 2
Transfer                       529.7 m              Lpp           139.35  m
Tactical Diameter             1074.4 m              Bwl            20.40  m
Steady Diameter               1170.9 m              T              5.500  m
Time for 90 deg turn          145.00  sec           Uini           18.00  knots
Time for 180 deg turn         260.00  sec           RUD2               0  deg
Time for 270 deg turn         375.00  sec           RArea           1.00  m2
Time for 360 deg turn           0.00  sec           PpOr           80.00  %
```

Figure 5: Input and Results for Frostisen Turning Circle Test

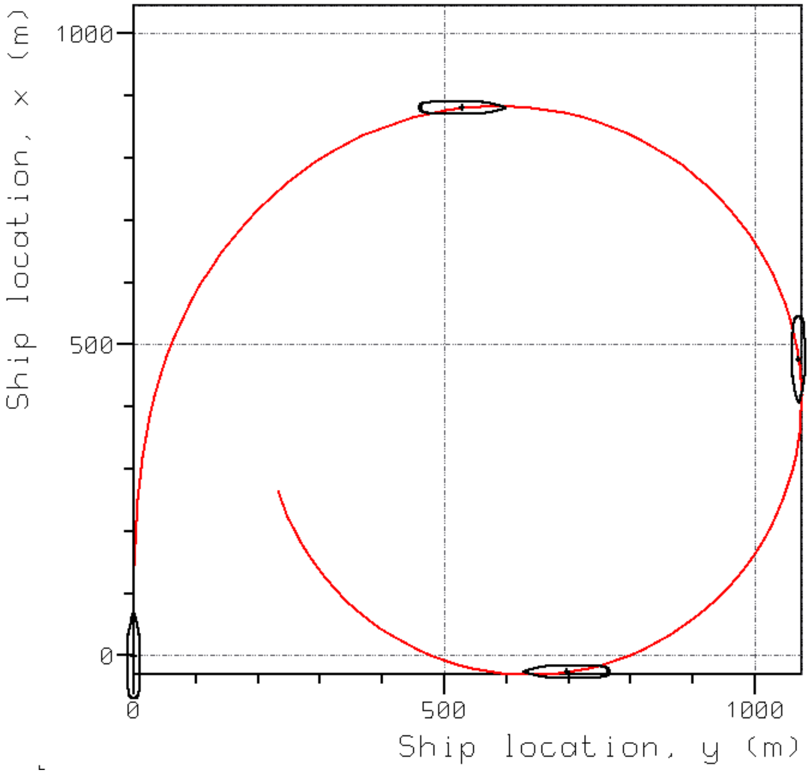


Figure 6: Diameter of turning circle at 18 kn is around 1000 m

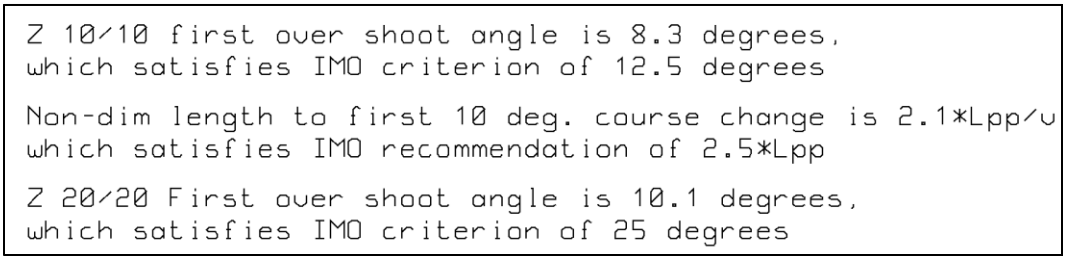
The results show that turning circle diameter at 18 knots is about 1000 m. Time for 180-degree turn is 4.3 minutes. The results seem reasonable.

The second test performed was zig-zag test, also at 18 knots. Figure 7 show input used for zig-zag test analysis.

```
wl length      139.32   m          Np              2
Bwl             20.40   m          Dp          3.850   m
T               5.500   m          P/D         1.397
block          0.5911              Ear         0.400
LCB            -1.270   m          RArea        1.00   m2
Uini            18.00   knots      RudHei       1.00   m
```

Figure 7: Input used for zig-zag test.

Results for zig-zag test are shown in Figure 8, Figure 9, and Figure 10. The first overshoot angle for 10/10 test is 8.3 degrees, which satisfies IMO criterion. The first overshoot angle for 20/20 test is 10.1 degrees, which also satisfies IMO criterion. The results seem reasonable as well.



```
Z 10/10 first over shoot angle is 8.3 degrees,
which satisfies IMO criterion of 12.5 degrees

Non-dim length to first 10 deg. course change is 2.1*Lpp/v
which satisfies IMO recommendation of 2.5*Lpp

Z 20/20 First over shoot angle is 10.1 degrees,
which satisfies IMO criterion of 25 degrees
```

Figure 8: First overshoot angles for zig-zag tests satisfy IMO criteria

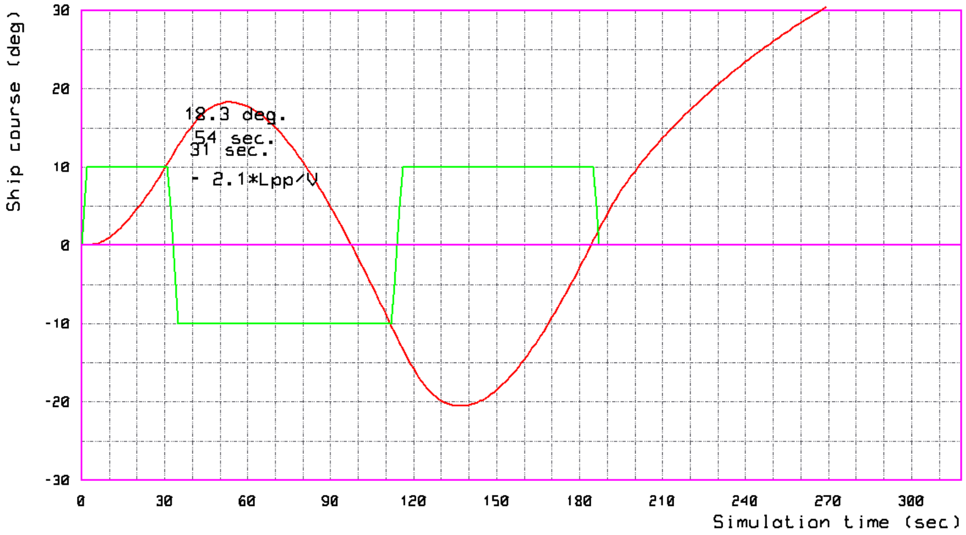


Figure 9: 10/10 zig-zag test satisfies IMO criteria.

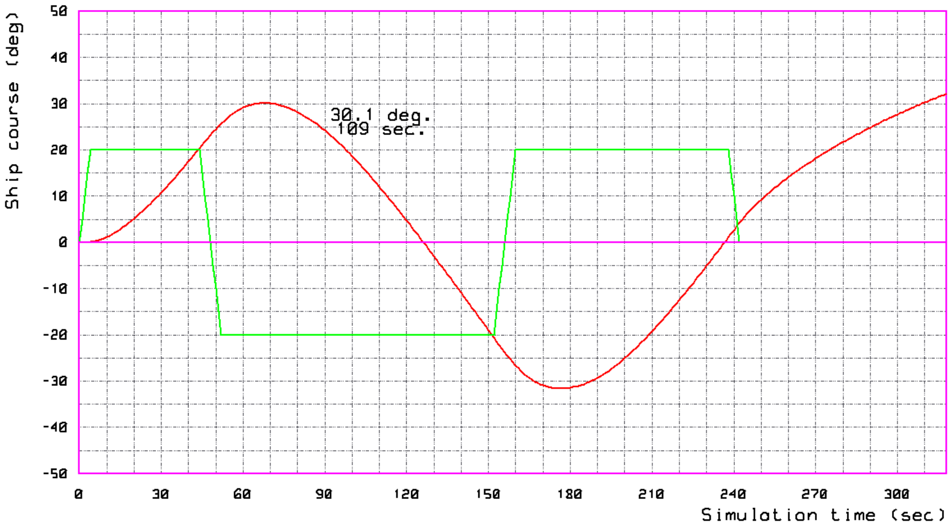


Figure 10: 20/20 zig-zag test satisfies IMO criteria.

5.4.2 Added Resistance

NAPA software was used to calculate the response amplitude operators for added resistance in regular and irregular waves. Calculations was made with 4 different speeds: 0, 10, 15 and 18 knots. Added resistance was calculated only on 180° heading. The following graph is achieved, and it represents RAOs in regular waves. The figure shows RAOs in sea state 4 including a 6 second zero-crossing period. It corresponds to Beaufort scale 5.

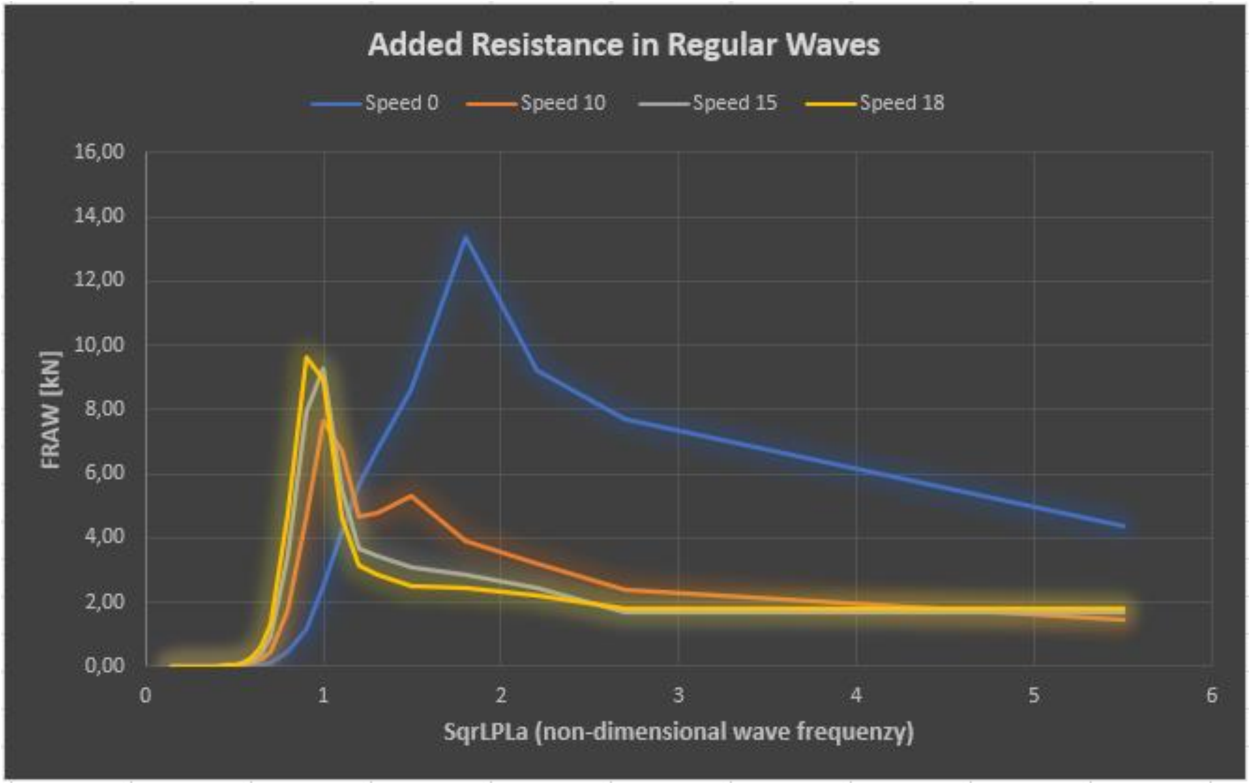


Figure 5.4-11 RAOs for Added Resistance in Regular Waves

It is simply notified that the added resistance increases with speed. Although the added resistance is greatly present when vessel speed is 0 knots at 180 degrees heading. The design speed of Frostisen is 17 knots and therefore, the values of 18 knots correspond well to ideal cruising speed. The added resistance reaches around 10 kN with that speed.

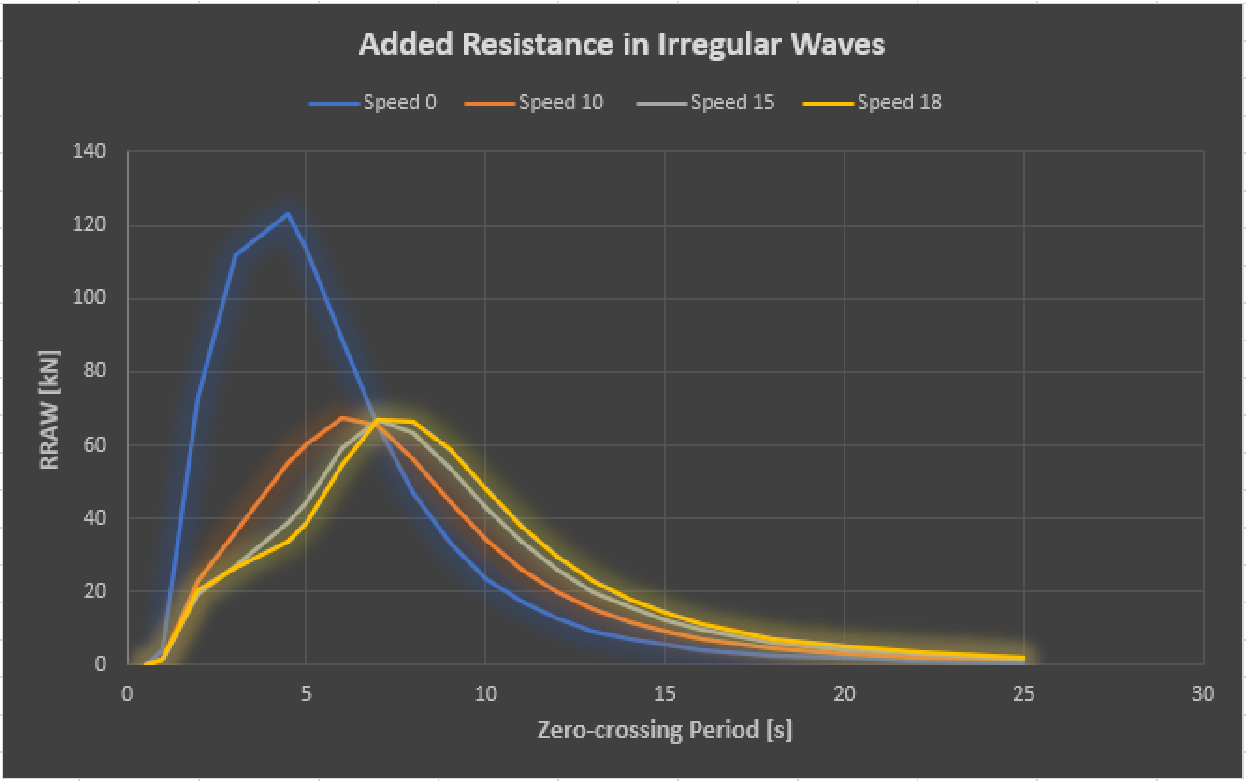


Figure 5.4-12 RAOs for Added Resistance in Irregular Waves

The values obtained for RAOs for added resistance in irregular waves are much higher than for regular waves. This is inevitable and predictable. However, speed doesn't really have that great of an impact in the values of RRAW.

Frostisen is equipped with two ABB Azipod DO1600P with power of 7,5 MW each, total power of 15 MW. The power estimation shows that with propulsion power of 13,1 MW, the maximum speed of 21 knots is reached. Therefore, there is relatively large margin in the power demand. Generally, it could be concluded that the added resistance would not be a problem of Frostisen.

From scientific literature, it is clear that the added resistance calculation is very important for a ship of this size. The article "On the prediction of the added resistance of large ships in representative seaways" by Liu and Papanikolaou say that "properly quantifying the spectral contribution of the added resistance in the region of λ/LPP 0.1~0.5 is of paramount importance." Traditional methods actually calculate the added resistance for wavelengths of 0.5-2 LPP. The accuracy and relevance of our results are called into question. Based on reference ships mentioned in the article, the values of our RAOs for added resistance are within an expected range. It seems that NAPA has calculated them well enough for the current standards, but perhaps that an analysis of shorter wavelengths would be beneficial to calculating added more accurately.

5.5 Improvements for Future Development

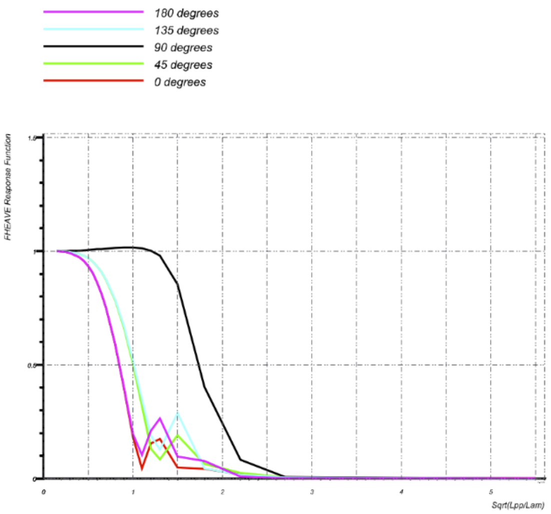
The roll motion is exceeded 15 time per hour at 15 knots, and more at 10 knots. Although this is a conservative estimate, it would be bad for the passenger comfort for the roll motion to be so high. The effect of the fin stabilizers is also unable to be modeled at this stage of our design. Improvements can therefore be made to the ship in the early design stage to reduce roll motion. The next stage of design could also include a more in-depth analysis of the effectiveness of fin stabilizers.

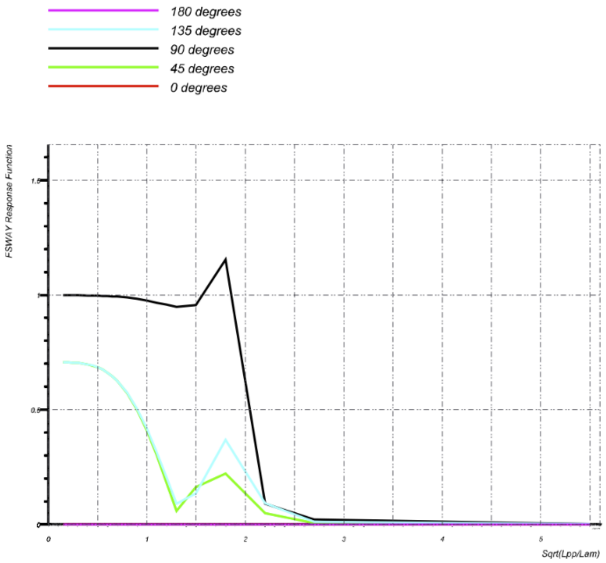
The motion sickness incidence is exceeded 12 times at head seas at 15 knots. The motion sickness could also be improved through design measures. Motion sickness is caused by heave motions and amplified in areas where the horizon cannot be seen. To reduce heave motions, the waterplane area should be reduced. The main factor affecting this in terms of hull form is the beam. By decreasing beam, the heave accelerations should decrease. However, by avoiding bad conditions or speeds, the problem scenarios can be avoided. The navigating officers should be made aware of the problem scenarios for the motion sickness and roll motions. The hull form does not necessarily need to be changed, but in the next iteration of the design can be improved for motions and maneuvering optimization.

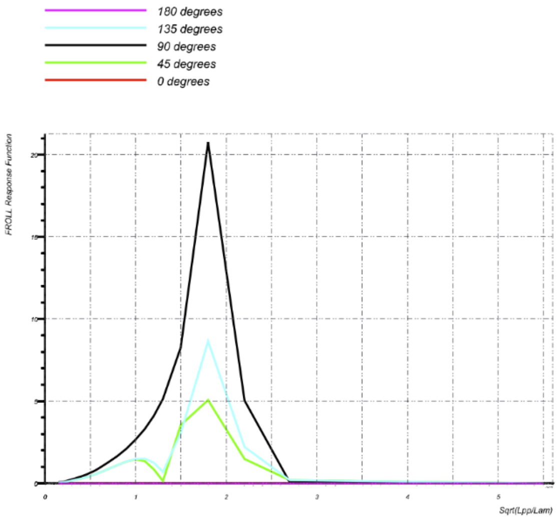
Another consideration in the future development of the dynamic assessment of Frostisen would be to include ice in the analysis. In arctic and Antarctic operations, some ice will be encountered. In this course, modeling ice flow is far to complex, but in the future some analysis of the impact of more complex environmental conditions could be explored.

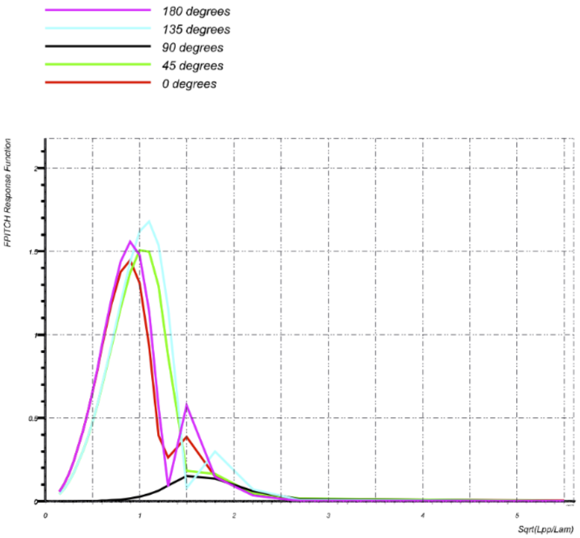
Appendix

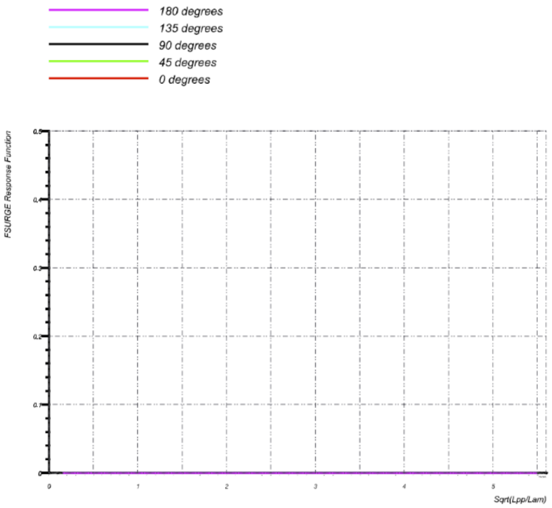
At zero knots:

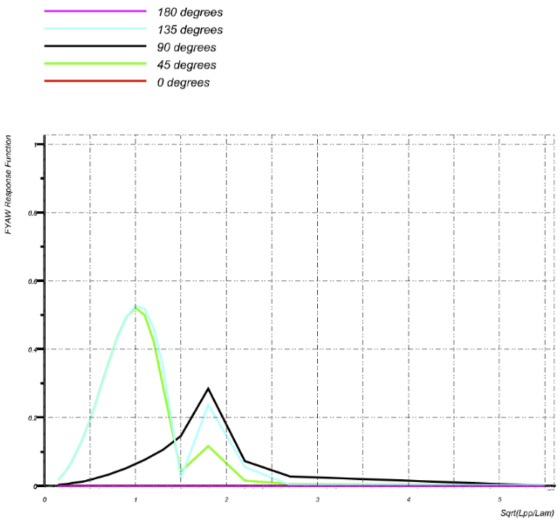




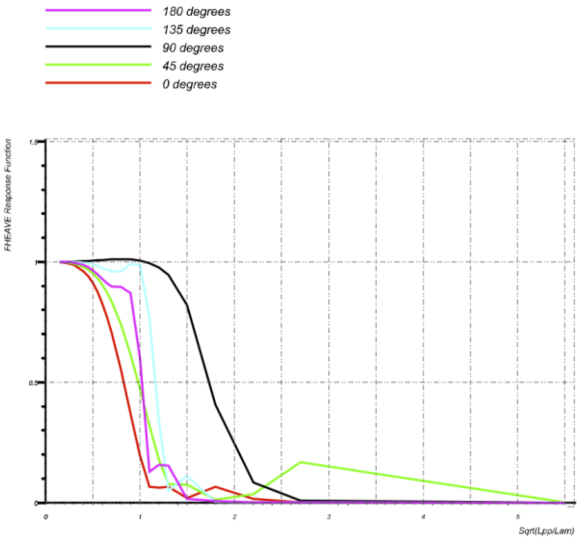


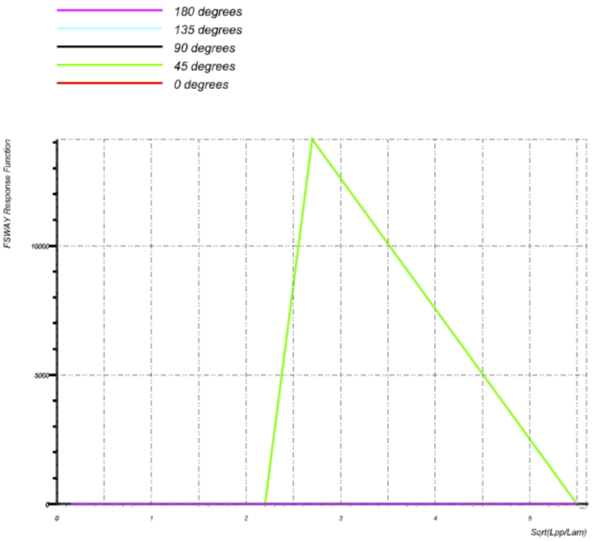


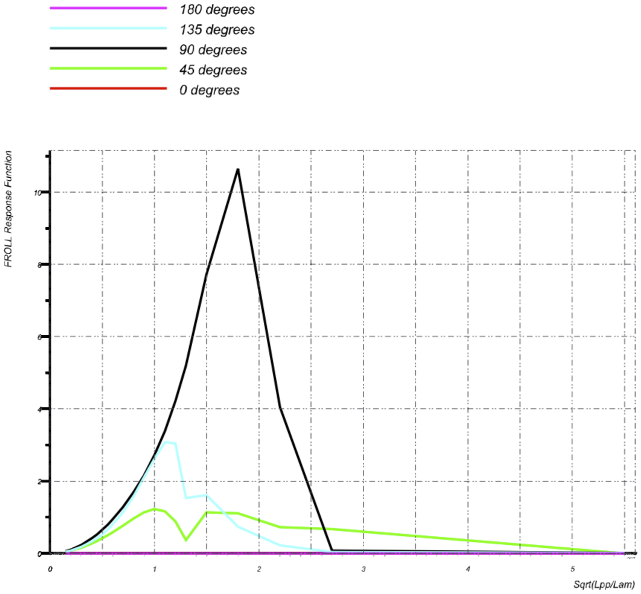

180 degrees
135 degrees
90 degrees
45 degrees
0 degrees
FSURGE Response Function
0
1
2
3
4
5
Sqrt(Lpp/Lam)

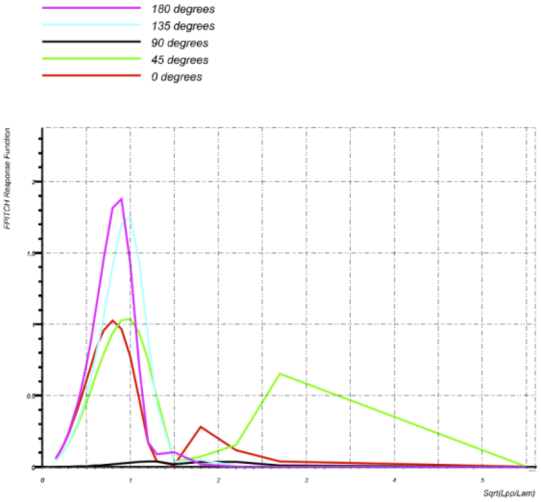

180 degrees
135 degrees
90 degrees
45 degrees
0 degrees
FYAW Response Function
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
Sqrt(Lpp/Lam)

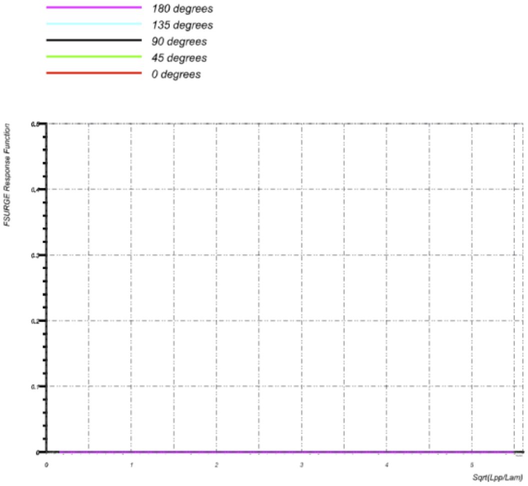
At 15 knots:

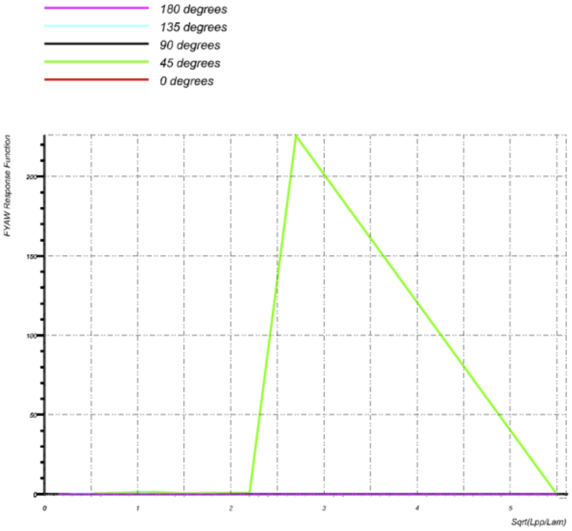

180 degrees
135 degrees
90 degrees
45 degrees
0 degrees
FHEAVE Response Function
1.5
1
0.5
0
0
1
2
3
4
5
Sqrt(Lpp/Lam)


180 degrees
135 degrees
90 degrees
45 degrees
0 degrees
FSWAY Response Function
10000
5000
0
0
1
2
3
4
5
Sqrt(Lpp/Lam)

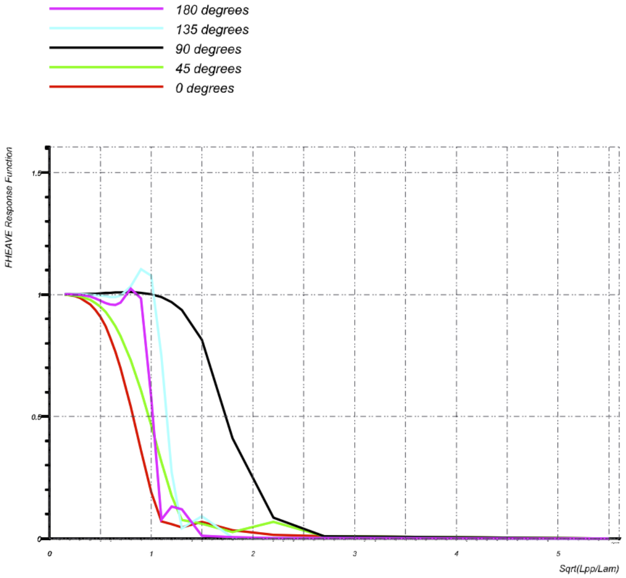

180 degrees
135 degrees
90 degrees
45 degrees
0 degrees
FROLL Response Function
0
2
4
6
8
10
0
1
2
3
4
5
Sqrt(Lpp/Lam)

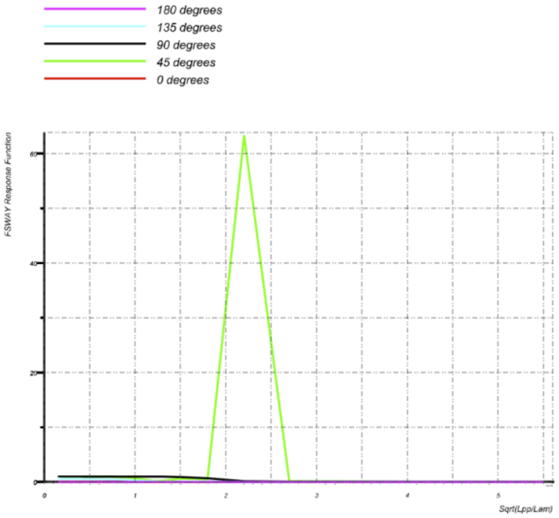

180 degrees
135 degrees
90 degrees
45 degrees
0 degrees
FPITCH Response Function
0
0.5
1
1.5
2
0
1
2
3
4
5
Sqrt(Lpp/Lam)

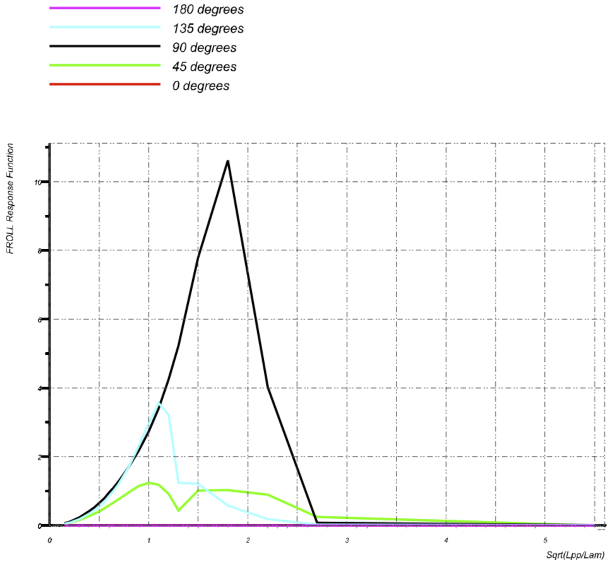

180 degrees
135 degrees
90 degrees
45 degrees
0 degrees
FSURGE Response Function
0
0.1
0.2
0.3
0.4
0.5
0
1
2
3
4
5
Sqrt(Lpp/Lam)

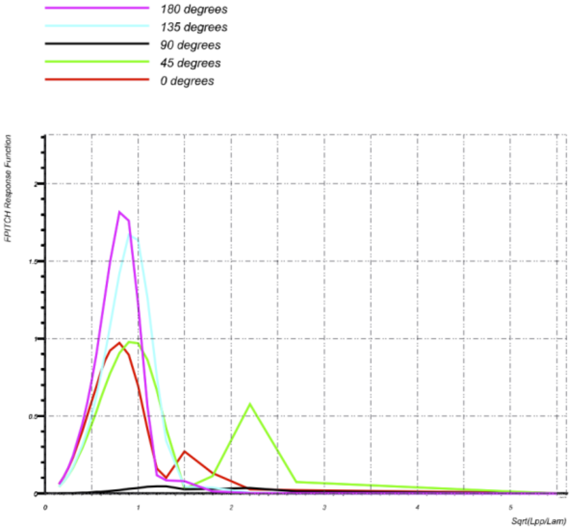

180 degrees
135 degrees
90 degrees
45 degrees
0 degrees
FYAW Response Function
0
50
100
150
200
0
1
2
3
4
5
Sqrt(Lpp/Lam)

At 18 knots:


180 degrees
135 degrees
90 degrees
45 degrees
0 degrees
FHEAVE Response Function
1.5
1
0.5
0
0
1
2
3
4
5
Sqrt(Lpp/Lam)


180 degrees
135 degrees
90 degrees
45 degrees
0 degrees
FSWAY Response Function
60
40
20
0
0
1
2
3
4
5
Sqrt(Lpp/Lam)


180 degrees
135 degrees
90 degrees
45 degrees
0 degrees
FROLL Response Function
10
8
6
4
2
0
0
1
2
3
4
5
Sqrt(Lpp/Lam)


180 degrees
135 degrees
90 degrees
45 degrees
0 degrees
FPITCH Response Function
2
1.5
1
0.5
0
0
1
2
3
4
5
Sqrt(Lpp/Lam)

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