M. Sc. THESIS

# Control Strategies for Maneuvering in Ice Ridge and Multi Ice Regimes

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# MASTER THESIS IN MARINE CYBERNETICS

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## FOR

## Sindre Ueland & Sverre Wendt Slettebø

Control strategies for maneuvering in ice ridge and multi ice regimes.

**Work description**

Operations in an arctic environment are dependent on accurate, safe and reliable Dynamic Positioning (DP) systems. Classical DP-systems are mainly designed for open water environment. This design can be non-optimal in ice regimes which are level ice, ice ridge, and broken ice floes. Different ice regimes may require different control strategies. The environmental loads can be rapidly changing with great magnitude dependent on the ice regimes and sea states in open water. Therefore, there is a need to switch between controllers when the ice and sea conditions change. Although DP operation in arctic area is important, the controller design and the switching strategy in ice have not been studied. The objective of this master thesis is to study the vessel's behavior and to propose the controller design for DP vessel operating in the arctic environment.

**Scope of work**

1. Create an ice ridge model with the purpose of calculating resistance of a vessel penetrating an ice ridge.
2. Expand the ice ridge model into a multi ice regime model, which also includes level ice.
3. Propose a new control structure for vessel manoeuvring or station keeping in ice ridge and multi regime ice conditions.
4. Perform simulations of the vessel operating in ice ridge and level ice.
5. Propose strategies for ice ridge penetration and crushing.

The report shall be written in English and edited as a research report including literature survey, description of mathematical models, description of control algorithms, simulation results, model test results, discussion and a conclusion including a proposal for further work. Source code should be provided on a CD. It is supposed that Department of Marine Technology, NTNU, can use the results freely in its research work, unless otherwise agreed upon, by referring to the student's work.

The thesis should be submitted in two copies within June 14th.

Professor Asgeir Sørensen

Supervisor

# Abstract

Operations in an arctic environment are dependent on accurate, safe and reliable Dynamic Positioning (DP) systems. Increased activities in arctic environments have lead to a demand for knowledge of different ice regimes and their affection on offshore structures and vessels.

The purpose of this master thesis is to create a simulation tool for interaction between an ice ridge and a marine vessel and to propose a special purpose DP-system for use in arctic environment. The thesis has been divided into two parts. First an ice ridge model was created in order to realistically simulate an interaction between a marine vessel and an ice ridge. Secondly several DP-tactics for station keeping in arctic environment was proposed and tested against the ice ridge model.

Different theories and calculation methods regarding resistance from an ice ridges have been discussed. An ice ridge model was proposed and discussed, and a parameter analysis of the ice ridge model was performed. Ridge size, ridge velocity and vessel dimensions were varied to investigate the total resistance. Simulations showed that that the ice resistance varied with the different parameters. It was shown that increased vessel width will gave an increased bow resistance, while the mid body resistance remained unchanged. Comparison with available literature proposes that the keel and sail contribution of the total resistance is small. Drawbacks with the ice ridge model have been discussed and further work proposed.

An open-water DP-system was created and supplied with different ice breaking features to ensure station-keeping in a ridge-vessel collision. Five different features was described and discussed. Simulations of station keeping have been performed using the ice ridge model. Simulations of the open-water DP-system were used as a reference and for comparison with the special purpose DP-system. The different ice breaking features were then discussed and compared.

The simulation study indicated that the open-water control system may not offer optimal performance when exposed to ice ridge forces and that a special purpose controller should be considered. For a marine vessel subjected to an incoming ice ridge, simulation results showed improved station keeping abilities with use of a special purpose controller. However, the special purpose controller proposed in this master thesis assumes detailed knowledge about the incoming ice ridge. For a real world system such detailed knowledge about an incoming ice ridge would require an advanced sensor system, something that have not been considered in this thesis but proposed for further work.

## Acknowledgements

This thesis is the result of the work performed by Sindre Ueland and Sverre Wendt Slettebø as the Master thesis at the department of Marine Technology at the Norwegian University of Science and Technology. The work has been done in spring semester of 2010 and has been supervised by Professor Asgeir J. Sørensen.

The work that has been done concerns modeling of an ice ridge and simulations of a vessel interacting with the modeled ice ridge. Several DP-tactics for use in arctic environment have also been proposed.

Much of the work has been done in SIMULINK and MCSim. We want to thank Morten Skogvold who generously spent much time giving us an introduction to MCSim. His help is much appreciated.

We would also like to thank Dr. Trong Dong Ngyuen and Petter Stuberg for advices and feedback given throughout the completion of this thesis.

Professor Kaj Riska pointed us in the right direction at a time where we were moving towards a "dead end". We would like to thank him for that.

Finally we would like to thank Professor Asgeir J. Sørensen for his general advices, specific contributions and for his help in keeping the spirit alive. It has been much appreciated.

Sindre Ueland, Sverre Wendt Slettebø

Trondheim, June 10th, 2010.

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# 1 Introduction

The aim of this thesis is first to model the ice resistance in the different phases of navigation through an ice ridge. Secondly a DP-system will be made in order to be able to test different tactics ice encountering. This chapter will present an overview of the background and motivation for this thesis together with previous work and published literature. The introduction ends with a presentation of contributions and outline of this report.

## 1.1 Background and motivation

The last hundred years there have been traffic in arctic seas and ice covered areas. Norwegian interests in ice covered areas have traditionally been related to fishing, whale hunting and polar expeditions. Other nations, like Russia, Finland and Sweden, have been relying on ice breaking to maintain the sea trade in winter seasons. Today, the interest for arctic areas, and hence ice going vessels, might be larger than ever.

### 1.1.1 Navigation in ice-covered seas

In the recent years the oil industry has shown an increased interest for the northern areas which have lead to increased activity. The increased interest of marine vessels in arctic environment is also motivated by the possibility of, in the future, using the North-East passage to shorten transport time between Europe and Asia. Transit in the North East and North West passage is relevant since they were recorded ice free for the first time in 2009 (Riska 2009), see Figure 1.1 and Figure 1.2.  Even though they have for some specific periods been considered ice free, they are not likely to be totally ice free, as a combination of broken ice, level ice and ice ridges must be expected. However, this is something that is relying on global warming and ice melting. Few investments are made on these assumptions, which leaves the oil and gas industry as the major motivator for the technological progress.


Figure 1.1 The ice cover in 1979


Figure 1.2 North East and North West passage ice free for first time, September 2008

Marine vessels that operate in these challenging areas will experience a variety of condition from ice free summers, icebergs and seasonal ice cover. During winter season these vessels will with a large probability experience encounters with different ice features.  To perform subsea operations, in any climate zone, a station keeping system is required. That may be with use of anchor lines or DP. When designing a system for station keeping in ice covered areas it is vital to have knowledge regarding the resistance represented by the different ice features. This master thesis focuses on one of these ice features, namely the ice ridge, and the resistance it represents.

### 1.1.2 Dynamic positioning and challenges when encountering ice

A DP-system is a computer controlled system that automatically maintains a vessel's position by using its own actuators, i.e. the propellers and thrusters. Position reference sensors, combined with wind sensors, motion sensors and gyro compasses, provide information to the computer pertaining to the vessel's position and the magnitude and direction of environmental forces affecting its position.

The computer algorithm contains a mathematical model of the vessel that includes information pertaining to the wind and current drag of the vessel and the location of the thrusters. This knowledge, combined with the sensor information, allows the computer to calculate the required steering angle and thruster output for each thruster. This allows operations at sea where mooring or anchoring is not feasible due to deep water or other problems.

Dynamic positioning is much used in the offshore oil industry, for example in the North Sea and off Brazil. Nowadays there are 2000-3000 DP vessels. Figure 1.3 on the next page shows a floating production, storage and offloading (FPSO) relying on DP-system and anchors for station keeping.

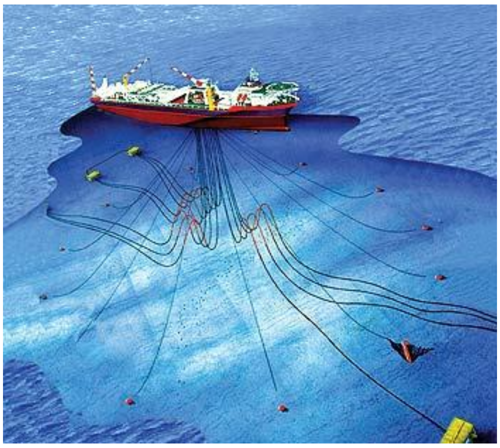

Figure 1.3 Vessel using DP and anchors to stay stationed

Dynamic positioning in ice covered areas calls for some extra measures. For instant, the integrator part of the control system is supposed to counteract static environmental forces.  But due to sudden changes in environmental forces in rapid changing ice conditions, the integrator have to be reset or emptied for every recorded significant change in environment forces.

A challenge for DP-systems is the need for knowledge about the ice before impact. Due to the large magnitude of the ice resistance, this is especially true for impact with ice ridges. As customary DP only uses wind measurements as a feed forward in the control system, a DP-system used in ice will benefit greatly of having some kind of knowledge about the ice before impact. This however raises new problems, an advanced sensors system is needed to measure ice properties, geometry and speed. The consequences of sensor malfunction or loss can pose a big threat to safety.

## 1.2 Previous work and published literature

Most of the available literature discussing ice ridge is from one of the two main periods regarding to ice research. The first period, late 1970`s and early 1980`s there were published a few articles about ice ridges. Arno Keinonen (1979) published “An analytical method for calculating the pure ridge resistance encountered by ships in first year ice ridges” and Mellor (1980) proposed equations for calculating ridge resistance.  Kovacs (1979) made a geometrical generalization of “the idealized” ice ridge, where he described relations between the different parts of the ice ridge.

The next “ice-period” was the mid 1990`s where several new actors proposed methods for load predictions, described mechanical properties of ice and performed model tests in ice. Timco and Brien (1994) proposed an equation for calculating the flexural strength of sea ice. Croasdale (1994) developed a wedge failure theory, where he described a failure mode for an ice ridge colliding with a cone shaped leg of an offshore structure.

The Canadian Hydraulic Centre, CHC, published in 2000 “an overview over first-year sea ice ridges” where they gathered available model test results, theory and calculation methods related to ice ridges. The methods for prediction ridge loads are mainly for the case of an interaction between an offshore structure and an ice ridge. Literature regarding interaction between a moving marine vessel and an ice ridge is very limited.

Literature for strategies for how to encounter ice ridges is found to be almost nonexistent.

## 1.3 Contributions

The aim of this master thesis is to describe the total ice resistance as a marine vessel interacts between an ice ridge and a marine vessel. Also different strategies to ensure small deviation from desired position are to be studied. In the attempt to do so the following has been done:

- An ice load SIMULINK model has been created in order to simulate ice ridge loads, ref chapter 6.
- The ice load model has been extended to also include a simplification of the of the already existing level ice model, ref Figure 7.7.
- There is an already existing SIMULINK model, Marine Cybernetic Simulator (MCSim), which simulates and calculates ice resistance for cases of level ice and broken ice. The ice load model has been implemented into the MCSim, ref chapter 0.
- In an attempt to describe the total resistance, a series of simulations are made to compare the load situations for different incidents. These simulations are done for various shapes and sizes of the vessel and the ice ridge, ref chapter 0.
- Different strategies for ice crushing and ice penetrating have been proposed, and studied, ref chapter 0.
- The strategies or tactics have been implemented into the SIMULINK model and have been run through a series of simulations in order to compare them with each other and also to compare them with the scenario where no strategies are used, ref chapter 11.

## 1.4 Outline of thesis

In order to get a quick overview over this thesis, a bullet list with each chapter and content are here presented.

- Chapter 0 gives a brief description of the ice ridge. The formation process and geometrical properties of the ridge is described and the different resistance aspects are discussed.
- Chapter 0 presents different methods for predicting ice ridge resistance. The relevance of these methods for this master thesis is discussed.
- Chapter 4 discusses the initial but rejected method for calculating ice ridge resistance in this thesis.
- Chapter 5 contains a detailed description about the method used in this master thesis to describe the resistance forces in an ice ridge. The theory is presented and the line of action is described.
- Chapter 6 presents the SIMULINK model with explanations and flowcharts.
- Chapter 7 explains how the ice loads are implemented in software used to simulate a vessel.
- Chapter 8 explains how the DP-system is implemented in the MCSim model.

- Chapter 9 present results from simulations using a customary DP-system. Here a customary DP-system means a system without any strategies for ice crushing or ice penetrating. DP-system and ice ridge loads are collected from previous chapters.
- Chapter 10 present different strategies for penetrating ice. These strategies are evaluated and discussed.
- Chapter 11 presents results from simulations using the different strategies developed in the previous chapter. These results are compared with each other and discussed.
- Chapter 12 concludes the report and evaluates the most important findings and recommends for further work.

# 2 Ice ridge

Ice ridges are one of the most common obstacles for marine vessels and offshore structures operating in arctic environment. The ice ridges can be found in different regions like the coast of Newfoundland and the Baltic Sea. An ice ridge can vary in size, shape and strength, which is determined by both age and formation process. It can float free in the ocean, be frozen into level ice or it can be found resting on the sea bed in ground water. Both from a structural design - and control system point of view an ice ridge is a considerable engineering challenge.

## 2.1 Formation process

An ice ridge is created by blocks of ice, snow, air and water, which is exposed to environmental forces. This can happen in two ways, either by compression or by shear stress. In both cases ice blocks and level ice are crushed, bended and piled up, both under and over the water line (keel and sail). Traditionally the ridges have been categorized by their mode of formation, either as a compression ridge or as a shear ridge. However, it is not always sufficient to look at the properties of a ridge to tell whether it is created by shear or compression. Therefore it is more reasonable to classify an ice ridge by age, from “First-year” to “Multi-year” ice ridge. A “First-year” ice ridge is made by poorly bounded individual ice pieces, with snow, water or air in between. A “Multi-year” ridge has survived several periods of melting and the core of the ridge consolidates as the gaps between the blocks are filled with water that freezes in winter time. In other words, the strength of the ice ridge increases with age. After surviving several melting periods the ice ridge will become a solid mass, and if frozen into level ice it represents the worst loading case for a marine vessel. Figure 2.1 shows the characteristic look of an ice ridge seen from above the waterline.

Figure 2.1 Ice Ridge in Antarctica (Salvesen 1990)

## 2.2 Ridge geometry and relations

As mentioned in the previous section an ice ridge is found in many different sizes and shapes. However, it is possible to divide an ice ridges into three parts.

- The sail
- The consolidated layer
- The keel

**The sail** is what would be observed from a vessel or an offshore structure. It consists of ice blocks piled up over the water line, forming a ridge. These ice blocks can be partially frozen together, or can be relatively unconsolidated.

**The consolidated layer** is created from refrozen rubble and/or rafted ice. This layer grows when the temperature is below the freezing point. However, the growth rate is faster than in level ice. Hence the consolidated layer of an ice ridge frozen into level ice will be thicker than the surrounding level ice. In a "Multi-year" ice ridge the consolidated layer will represent the biggest resistance component in a vessel-ice ridge encounter. For a "First-year" ice ridge the consolidated layer will be non-existent or very thin.

**The keel** is found under the waterline and hence cannot be spotted from a vessel or offshore structure**.** Similar as the sail, the keel is comprised of a large numbers of ice blocks, but it is significantly larger than the sail. This part of the ice ridge will with aging turn into a consolidated layer, as the ice blocks and the water in between freezes into a thick layer of ice.

Figure 2.2 shows an ice ridge grown into level ice. The sail and keel of the ice ridge can easily be spotted. The thickness of the consolidated layer equals the thickness of the level ice in addition to the growth due to aging.

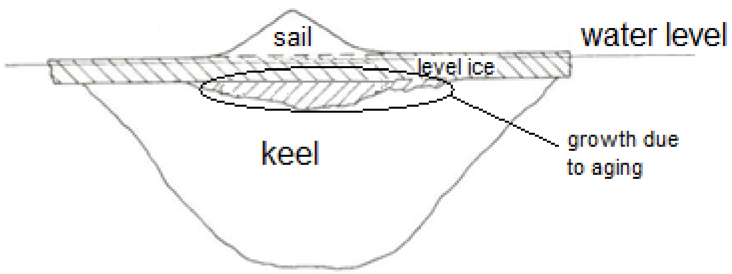


Figure 2.2 Sail, consolidated layer and keel (Keinonen 1978)

Ice ridges are commonly found frozen into level ice. A special property of an ice ridge frozen into level ice is that the consolidated layer in an ice ridge is thicker than the surrounding level ice. The consolidated layer in the ice ridge has a larger growth rate than the surrounding level ice, illustrated by Figure 2.2.

As a rule of thumb the consolidated layer within the ice ridge is approximately 1.8 times thicker than the surrounding level ice (Riska, 2009). The reason for the fast growth of the consolidated layer is the property of the mixture of rubble, air pockets and water in the ridge keel. This mixture seems to freeze at a faster rate than the pure water below the level ice. This property is very important to consider when doing resistance calculations for an ice ridge.

## 2.3 Ice resistance

There are three key factors to consider when navigating a marine vessel through an ice ridge:

- A vessel penetrating an ice ridge will experience a resistance force opposite of its motion. This resistance is a sum of friction force, submersion force and crushing force.
- The ice might in some cases exert a negative effect on propulsion, with rubble and bigger pieces interfering with the propeller revolution.
- Inertial effects (added masses, accelerations in vertical and horizontal directions) will play a role in ice crushing.

In this thesis only the resistance problem is considered. Although the inertial effects will play a role in the resistance force calculations, the effects are in this thesis kept separate for the sake of simplicity. The possible occurrence of ice affecting the propulsion is also neglected.

The ice resistance forces have many factors to be considered, in this thesis the focus will be on three separate key components:

- Resistance due to ice crushing, $R_{Crushing}$
- Resistance due to ice submersion, $R_{Submersion}$
- Resistance due to friction with ice, $R_{Friction}$

By the superposition principle the total ice resistance is found,

$$R_{ICE} = R_{Crushing} + R_{Submersion} + R_{Friction} \tag{2.1}$$

Many factors will influence the total ice resistance when a marine vessel encounters an ice ridge. Ice thickness and ice strength are two obvious parameters. The ice thickness is a pure result of the environmental temperatures and is increasing the ice crushing resistance as it gets thicker. Ice strength will depend on the salinity and environmental temperatures. Strength of ice with a certain thickness may vary a great deal. Samples and laboratory tests have shown that salinity and the growth rate of the ice will be the determining factors of the ice strength (Riska, 2004). Vessel velocity and friction type, will affect the total friction force resistance. Ice density influences the buoyancy forces of submerged ice blocks and will affect the total submersion resistance.

Table 2.1 shows the connections between five important parameters and the three main resistance components.

| | | Parameter | | | | |
|---|---|---|---|---|---|---|
| | | Ice strength | Ice thickness | friction | velocity | Ice density |
| Main resistance component | Ice crushing resistance | X | X | X | X | |
| | Ice friction resistance | | | X | | |
| | Ice submersion resistance | | X | | X | X |

Table 2.1 Connection between important parameters and resistance components

### 2.3.1 Resistance due to ice crushing, $R_{crushing}$

The crushing resistance occurs at impact between the vessel bow and a solid ice body. Ice crushing resistance will last for as long as the bow is penetrating ice. The impact between the vessel bow and the ice body will crush the ice body into small rubble and bigger ice blocks. Such impact will exert a resistance force opposite to the vessels direction of motion. The crushing resistance will depend of the ice body's mechanical properties i.e. the ice thickness and ice strength.

### 2.3.2 Resistance due to ice submersion, $R_{Submersion}$

After the initial vessel-ridge impact, the ridge will be broken into pieces. There will be rubble, and ice blocks have to be removed from the vessels path. Due to shape of the bow some of the ice rubble will be pushed downwards; submerged in water. As a result the vessel will encounter resistance due to submersion of ice blocks. This resistance is a result due to the fact that ice blocks in the bow area are gaining hydrodynamic support. Figure 2.3 illustrates how the submersion resistance is created.

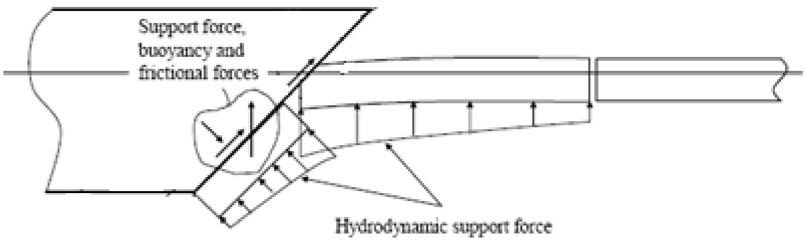


Figure 2.3 Resistance components (Riska 2004)

### 2.3.3 Resistance due to friction with ice, $R_{Friction}$

A friction force is caused by the relative lateral motion of two solid surfaces in contact i.e. the vessel hull and the ice edge. For the case of a vessel penetrating an ice ridge two cases of friction will appear, dry friction and wet friction. The wet friction is caused by large blocks of ice that are piled up under the waterline. These blocks are being pushed towards the vessel hull by the buoyancy force and constitute a frictional resistance to the vessel movement.

Figure 2.4 illustrates how ice rubble stuck under a vessel hull will cause frictional force as the buoyancy force pushes the ice rubble against the hull and the more common situation of ice causing dry friction on the hull sides.

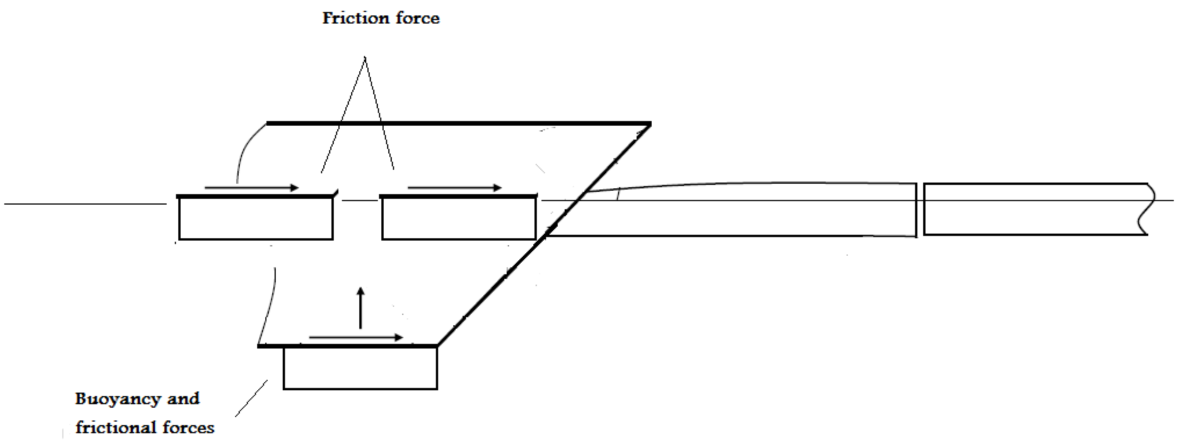


Figure 2.4 Wet- and dry -friction

When a vessel is navigating in level ice, the bow and mid body area will be surrounded of ice above the waterline. The lateral relative movement between this ice and the vessel is creating the dry friction. The dry friction is the major part of the frictional resistance. To reduce this resistance most ice going vessels are coated with ice resistant coating and stainless steel compound plates.

Several creative attempts have been made to reduce the dry friction, for instants an air bubbling system or a water fall system, as shown in Figure 2.5.


Figure 2.5 Waterfall system (Riska 2004)

# 3 Methods for predicting ridge resistance

There have been a number of different approaches to predict the resistance exerted by ridges on offshore structures and vessels. These can be categorized into three main groups which will be described in this chapter:

- Model tests
- Analytical models
- Numerical models

## 3.1 Model test

Model test programs are able provide excellent insight to the interaction of ice ridges with structures and vessels. One of the most challenging aspects of tests involving an ice ridge, is the production of a realistic ridge in the model basin. Many different attempts have been made to create a realistic model of the ice ridge, but this aspect yet remains as the main element of uncertainty for model tests.

Model tests results regarding vessel interaction with ice ridge are not readily available. However model tests have been carried out to investigate the failure behavior of ridges and the associated loads during interaction with fixed structures. Some of these results can be transferred to the case of vessel interaction with an ice ridge.

Timco and Cornett (1995) performed a model test program of the interaction of first-year ridge with a pier. In this test program, there were a number of observed failures modes for the ridge, the most relevant are listed under.

- Large-scale lifting of the ridge
- Circumferential cusp failure
- Ploughing failure

**Large-scale lifting of the ridge**

In the case of large-scale lifting of the ridge the central portion of the ridge was lifted as it slid up the face of the cone. This mode was only observed when the consolidated layer was very strong and the ridge had sufficient strength to enable it to be lifted up from the water. This failure mode produced high loads. Figure 3.1 shows the large-scale lifting of the ridge.

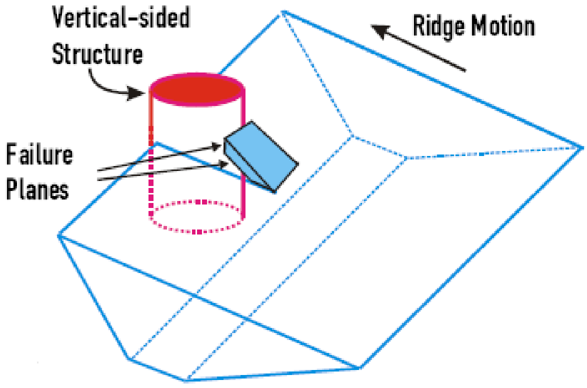


Figure 3.1 Large scale lifting of the ridge

**Circumferential cusp failure**

Circumferential cusp failure is caused by the conical section of the pier which induces circumferential cracks in the consolidated layer of the ridge. This failure created a number of semi-circular shaped ice pieces that were pushed against up the face of the cone as the ridge advanced towards the pier.

**Ploughing failure**

In a few cases, a "ploughing" type of failure pattern was observed. In this case, relatively small pieces of ice were broken in the region close to the pier. This mostly occurred with weaker ice. This is a common behavior for vessels navigating in ice, leaving the wake with small pieces of crushed ice, called brash ice.

Model test results are not yet readily available for a vessel-ice ridge encounter. This means that not all aspects of such an incident are taken into account. However, some of the results from the pier-ice ridge encounter can be used to foresee the breaking pattern of an ice ridge penetrated by a vessel. Further model testing should be done in the future to ensure valid results for a vessel navigating through ice ridges.

## 3.2 Analytical models

Analytical models of ice ridge resistance usually divide the ridge into three separate components, the consolidated layer, sail and keel. Loads are determined separately for each of the ridge components, and then, by superposition, the total resistance loads are found as a sum of each of the three resistances. The advantages of the analytical models are simplicity, but a lot of assumptions and simplifications have to be made which may give an uncertain result.

The different analytical models take different properties of the ice ridge and the encountering structure into account. This leads to different results from the different models. Figure 3.2 illustrates the big variations in the resistance results of analytical models. The ice properties, thickness and vessel data are identically for all the different models. Even so, by comparing two extreme methods, the resistance force for high speed will differ with a factor of almost two. In the figure $R_I$ is represented as the ice resistance, *v* the vessel speed, *h* the ice thickness and $\sigma_f$ describes the breaking strength of the ice. The labels on the right indicate which scientists that have provided each model. Poznyak did two experiments with different friction factors, marked as Poznyak 1 and 2 in the figure. Note that these results are resistance in level ice, not resistance encountering ice ridges. Even though, the figure still proves the point of huge deviations in analytical models for ice resistance calculations.

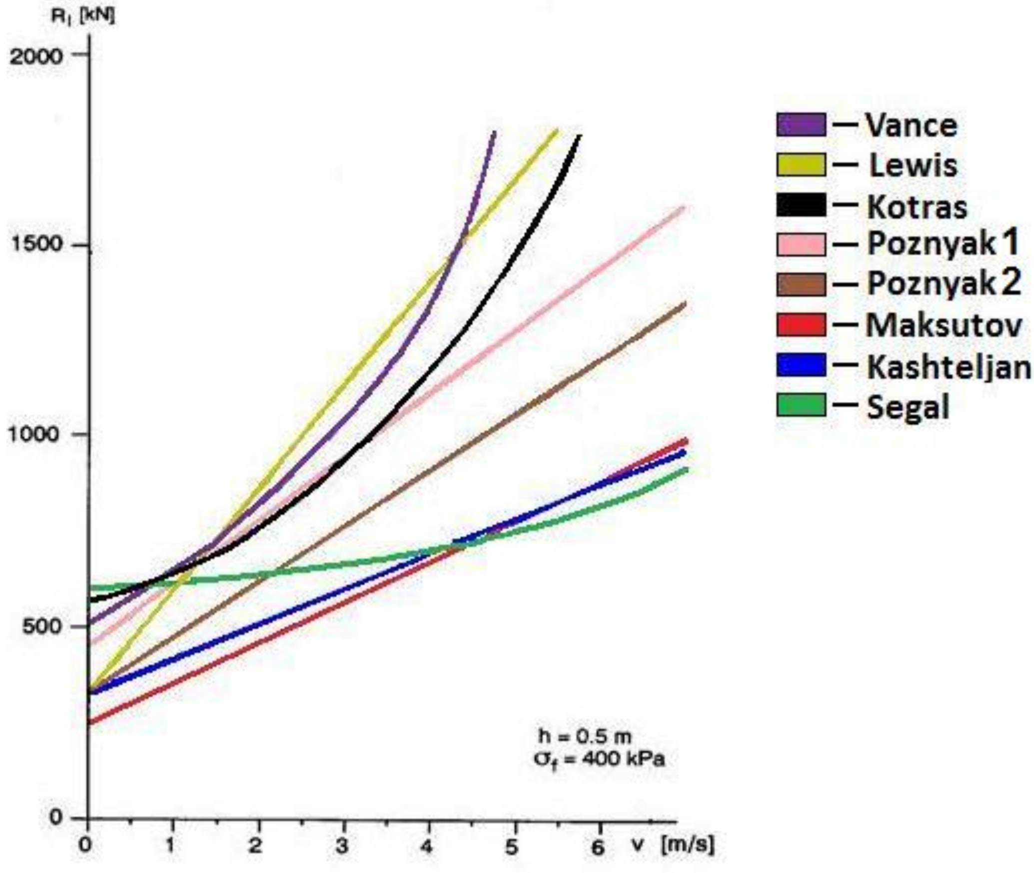


Figure 3.2 Different methods for predicting ice resistance (Riska 2004)

The variations in the results of the analytical methods are an indication on the fact that analytical methods might give inaccurate results. However, it also emphasizes the importance of knowing which method that should be used for each type of structure and ice load situation.

Mellor (1980) and Hoikkanen (1984) both have proposed each recognized analytical resistance models for an ice ridge. Both models include both sail and keel properties, which make these models presumably accurate. Prodanovic (1979) proposed a method which is recommended by the American Petroleum Institute (API, 1994). However both Prodanovic`s and Hoikkanen`s method are exclusively for offshore structures. In this thesis the ice resistance calculations will be done by Mellor`s (1980) method.

## 3.3 Numerical models

There are two numerical methods that have been used in order to do resistance calculations on ice ridges.

- Finite element modeling
- Discrete element modeling

### 3.3.1 Finite element modeling

Finite element method can be used to make estimates of global loads. However the method does not realistically represent the ridge failure process. The models have some assumptions that are not realistic and will give an error in the failure mode. For instants the keel is assumed to be of homogenous density and material, which is in correct, as the keel consists of consolidated layer and different properties throughout its body. This assumption together with some simplification necessary to perform FEM analysis, leads to the loads from the keel being over estimated. Problems regarding modeling of the material properties of the consolidated layer also lead to uncertainties in load estimates.

A few known cases with use of finite element modeling exist. Brown and Bruce (1995) modeled the interaction between a ridge and a pier. Figure 3.3 shows the different elements of the ice ridge model.

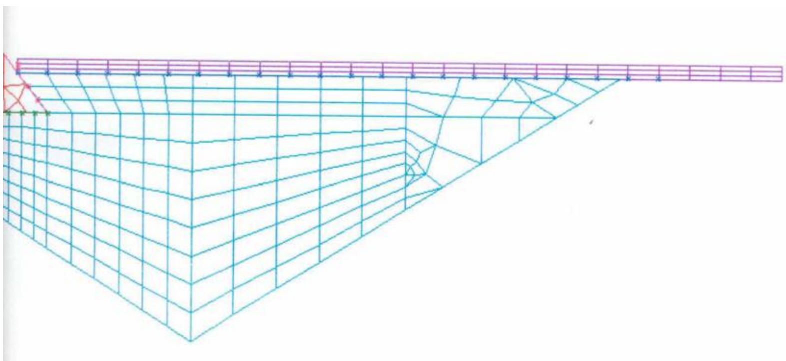

Figure 3.3 Finite element grid of an ice ridge interacting with a pier (Brown and Bruce 1995)

### 3.3.2 Discrete element modeling

A more commonly used method than the finite element modeling is the discrete element modeling. There have been done several analyses with use of this method. The discrete element method was for instants used by Sayed (1995, 1997) to investigate the failure of a ridge colliding with a pier.

The discrete models have several advantages compared to the finite element model:

- The interaction conditions between ice blocks are realistic.
- Accurate description of the ice edge.
- Deals with large deformations.
- Handles the discontinuities that usually arise during failure.
- Based on simple assumptions and avoid the uncertainty regarding complex constitutive equations.

Figure 3.4 shows the discrete modeling of an ice ridge keel colliding with a pier. This model differs from the finite element model by the fact that the keel is not modeled as a uniform body, but allows a more realistic model representation.

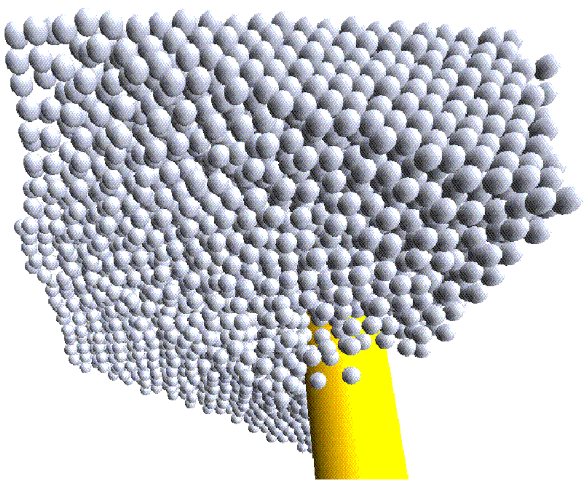

Figure 3.4 Ice ridge keel after impact with a pier (Sayed 1995)

The drawback with the discrete modeling method is the excessive need for computational power in order to produce a useful result. To analyze the loads on a vessel hull or an offshore structure this method is considered to be very good. In terms of a control system, there might be simpler methods that require less computational power.

# 4 Method A: Ice loads based on Mellor's formulas, distribution by a simplified model

The prediction of ice ridge loads will in this thesis rest on an analytical method. The initial method is inspired of a simplified model from Kaj Riska's lecture notes, see Figure 4.1. This figure is based on model tests results. It shows the force distribution as a function of bow penetration. The model is based on the assumption that different stages of penetration will give different values of resistance. The bow is divided into three different sections, in this chapter only referred to as *Bow1*, *Bow2* and *Bow3*. Where *Bow1* is the foremost section of the bow, *Bow2* the midsection and *Bow3* the hindmost section of the bow. All sections are according to the model about the same length, the length of the bow is therefore simply divided into three. Also note that the model assumes that the maximum resistance, $F_{max}$ is already calculated.

In Figure 4.1 $F_{max}$ is the total resistance, $F_{bow}$ the maximum resistance from the bow, $F_{midbody}$ the maximum resistance from the mid body, $L_{ridge}$ the length of the ice ridge and $H_{ridge}$ the height of the ice ridge.

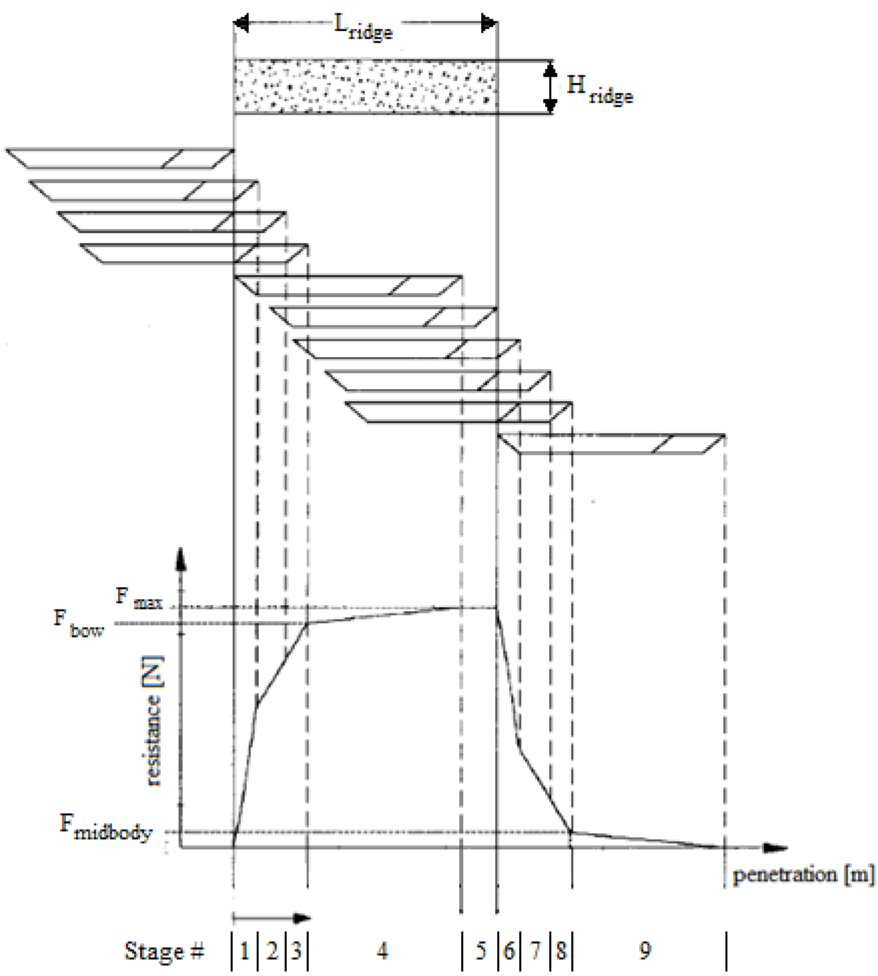


Figure 4.1 Resistance from Kaj Riska's model

**Stage 1:** Describes the situation where only the first part of the bow, *Bow1* has penetrated the ice ridge.

**Stage 2:** At this stage all of *Bow1* and some of part *Bow2* are in contact with ice.

**Stage 3:** The hindmost part of the bow, *Bow3* has started to penetrate the ice.

**Stage 4**: The ice ridge has passed the bow, and the mid body is now in contact with ice. This stage last until the whole vessel is in contact with ice.

**Stage 5**: This stage is the part when the whole vessel is in contact with the ice ridge.

**Stage 6**: *Bow1* is leaving the ice ridge.

**Stage 7**: *Bow2* is leaving the ice ridge.

**Stage 8**: *Bow3* is leaving the ice ridge.

**Stage 9**: Includes the situation from where the bow has left the ice ridge until the whole vessel has left the ice ridge.

In an early stage this model was considered, but after discussion with Kaj Riska it was rejected due to little flexibility and many uncertainties.

## 4.1 Resistance distribution

The model operates with different stages of penetration. Each stage has a different slope for the resistance, as shown in figure 4.1. All slopes are assumed to be linear. By running the SIMULINK model the resistance is graphed as shown in figure 4.2:

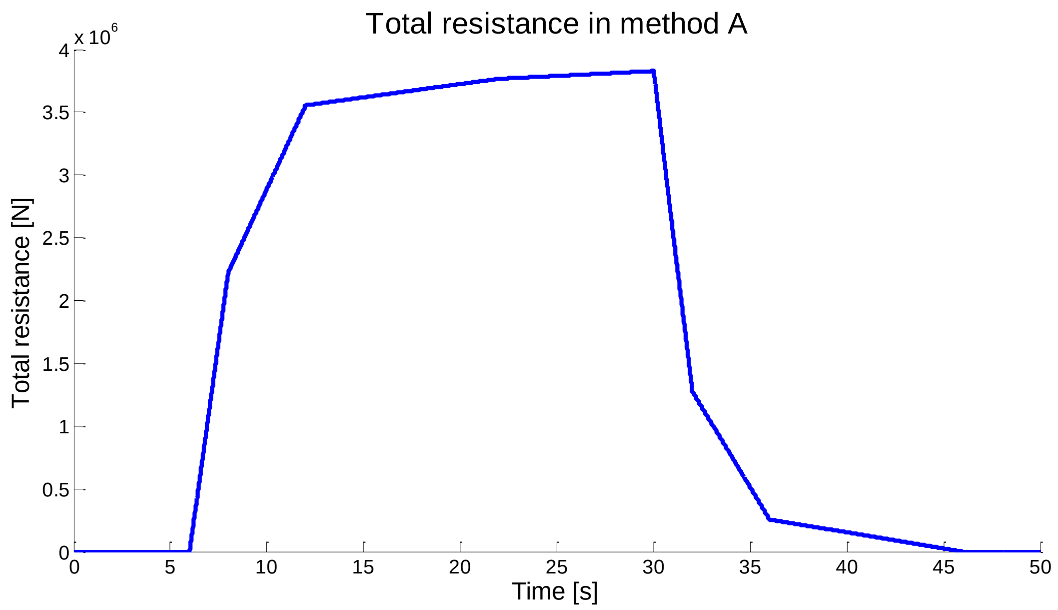


Figure 4.2 Total resistance with use of method A

## 4.2 Discussion of method A

The main benefit of this method is the simplicity. It is a fast way of getting some information about the resistance. The method indicates that dividing the resistance into several stages depending of the degree of penetration may be a way to simplify the problem. This thought is brought on to the method B.

Method A corresponds well with the model test (Riska 2004), as seen in figure 4.3.

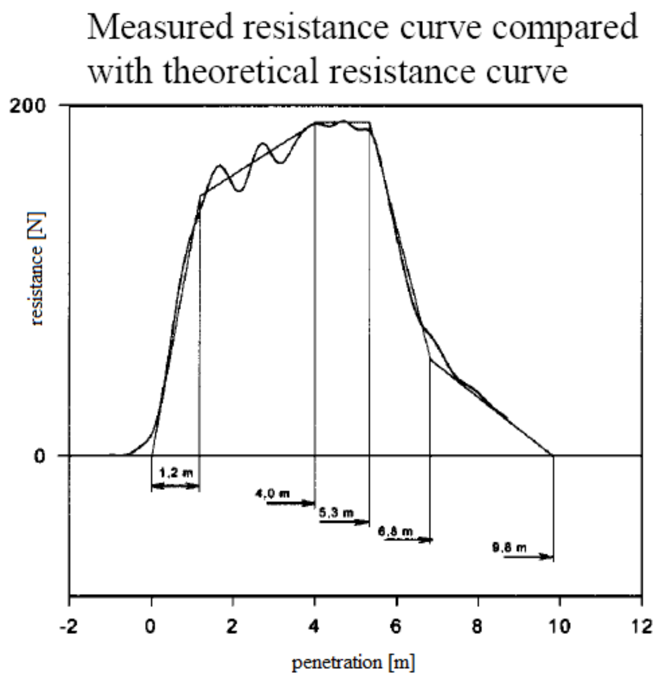


Figure 4.3 Ice resistance from the model compared with experiments

The main drawback however, is the rigid style the method provides. This model will not accept an ice ridge shorter than the length of the vessel. Also an increased ice ridge length will give the same resistance distribution, which is unrealistic. Additionally, the model does not take the vessels characteristics into account. With this in mind, the model does not provide a good enough resistance picture for the purpose of this thesis and the method is therefore rejected.

# 5 Method B: Ice loads based on Mellor's formulas, distribution by an analytical model

## 5.1 Introduction

Malcolm Mellor introduced in 1980 the paper "Ship resistance in thick brash ice" where the resistance was divided into two parts; bow resistance and mid-body resistance. His paper does not factor in the consolidating layer, which arguable can be approximated as level ice. A method for calculating resistance in level ice is already implemented in MCSim. MCSim will be closely described in chapter 0. The chapter's main focus is on the keel and sail contribution to the total resistance. Level ice resistance will also be briefly discussed.

Mellor's formula for the resistance is based on the idealized ice ridge model. It does only calculate the maximum resistances, not how the resistance varies with time. By combining calculations and assumptions on how the resistances behave, a good model can be obtained.

## 5.2 Defining yield resistance

Before the resistances can be calculated it will be helpful to define *R*, which is the yield resistance of the ice as given by equation (5.1) (Mellor 1980). Once the yield point is passed some deformation will be present. The normal force when penetrating ice is assumed to be the yield resistance, uniformly *R* per unit width,

$$R = \frac{1+\sin(\phi)}{2(1-\sin(\phi))}(1-\eta)\rho_i g(1-\frac{\rho_i}{\rho_w})t^2 , \tag{5.1}$$

where $\varphi$ is the internal friction angle, $\eta$ is ice porosity, $\rho_i$ is the density of ice, $g$ is gravitationally acceleration, $p_w$ is density of water and $t$ is the ice thickness.

In an ice ridge, the thickness, *T(x)* varies with the degree of penetration, by use of the idealized ice ridge model the relationship between thickness and the degree of penetration is easy to establish. See Figure 5.1

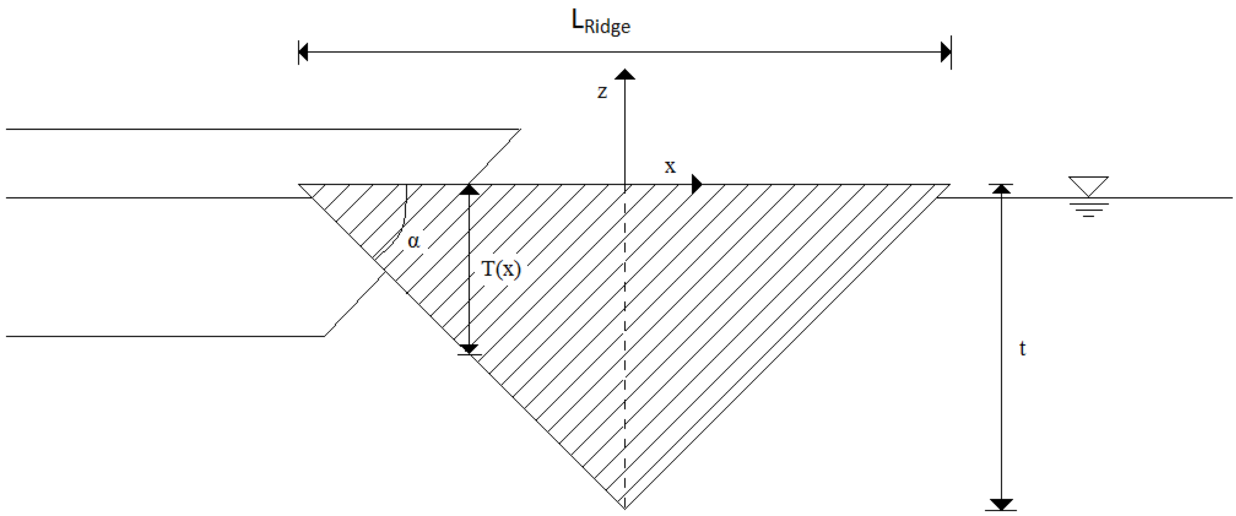


Figure 5.1 Thickness as a function of penetration with use of simplified geometry

For simplicity only ice ridge is considered in this figure, as the purpose of the figure is to establish how the thickness various with the degree of bow penetration of the ice ridge. A more realistic scenario will be to encounter an ice ridge frozen into level ice.

By Figure 5.1, including symbols;

$$\tan(\alpha) = \frac{T(x)}{L_{Ridge}/2 - |x|} = \frac{t}{L_{Ridge}/2} . \qquad (5.2)$$

Which solved with respect to T(x) gives

$$T(x) = t(1 - \frac{2|x|}{L_{Ridge}}) . \qquad (5.3)$$

Inserting equation (5.3) into equation (5.1) gives

$$R = \frac{1+\sin(\phi)}{2(1-\sin(\phi))}(1-\eta)\rho_i g(1-\frac{\rho_i}{\rho_w})(1-\frac{2|x|}{L_{Ridge}})^2 t^2 . \qquad (5.4)$$

*R* has a maximum value in *x=0*, when the ice ridge is at its thickest. The function has value zero in *x = +- $L_{Ridge}$/2* which satisfies the boundary condition. Also note that *R* is a function of the thickness squared. The yield resistance will be used to calculate the bow and mid body resistance in the following sections.

## 5.3 Bow resistance, $R_{Bow}$

Remember from Chapter 2.3 that the ice resistance could be expressed as

$$R_{ICE} = R_{Crushing} + R_{Submersion} + R_{Friction} \,. \tag{5.5}$$

The bow resistance appears whenever ice is in contact with the vessel bow. Figure 5.2 shows an example of this phenomenon. Further bow resistance consists of crushing and friction resistance and submersion. Submersion, however, consists mainly of friction and is therefore included in the frictional resistance term. Therefore the bow resistance reduces to

$$R_{Bow} = R_{Bow\_crushing} + R_{Bow\_friction} \,, \tag{5.6}$$

Where $R_{Bow\_crushing}$ is the crushing resistance in bow, and $R_{Bow\_friction}$ is the frictional resistance in bow, both evaluated in the following sections.

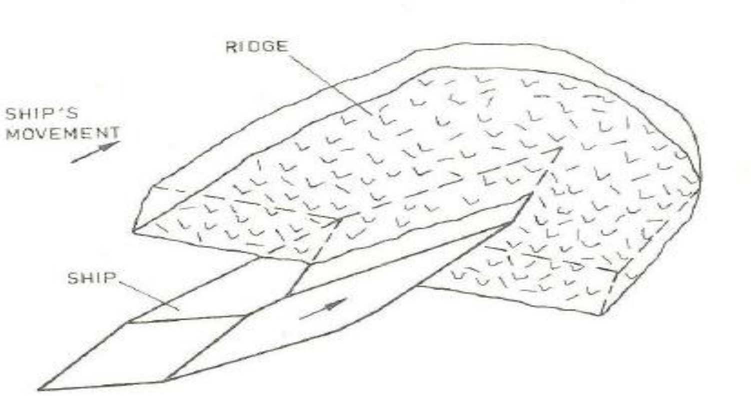


Figure 5.2 Situation with bow resistance only

### 5.3.1 Crushing resistance in bow, $R_{Bow\_crushing}$

The crushing resistance comes from the fact that the bow is plowing its way through the ice. By assuming a slender wedge the action is not much different from a smooth vertical plate pushed into ice. It is convenient to establish some geometric variables to easier see why the formulas are build up as they are. For the crushing resistance these variables are shown in Figure 5.3. Notice that the formula for the crushing resistance does not account for different bow shapes, with this simplified formula it is therefore sufficient to look at a bow with no curving.

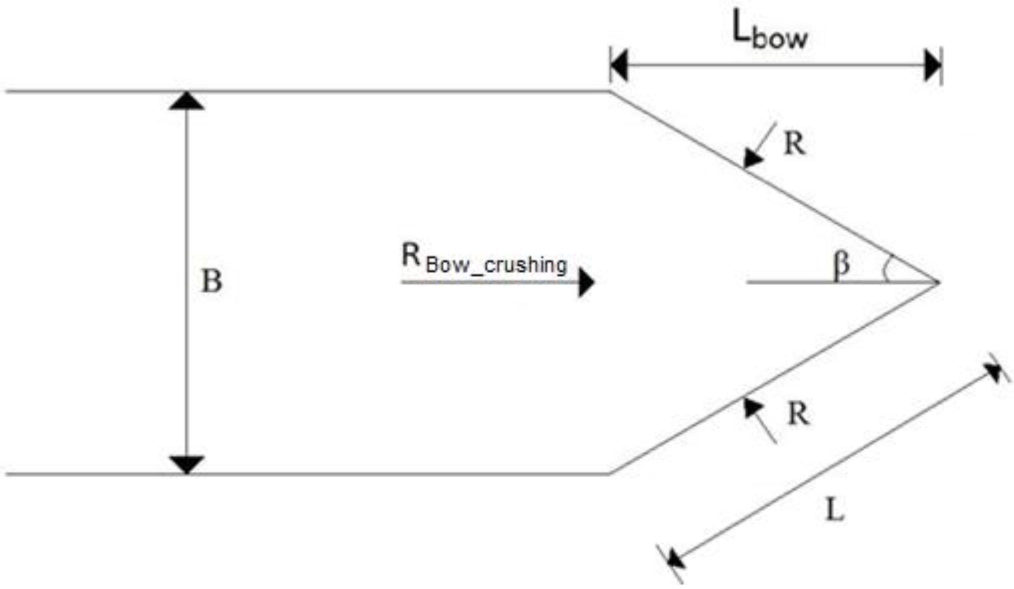


Figure 5.3 Slender smooth wedge pushing horizontally into ice ridge

*B* is the vessels breadth, *β* is the waterline angle, *R* is yield resistance, $R_{Crushing}$ is the crushing resistance in the direction of motion, and $L_{bow}$ is the length of the bow.

From the Figure 5.3, *L* can be found by simple geometry. First an expression for the angle is found

$$\sin(\beta) = \frac{B/2}{L}. \tag{5.7}$$

Solved with respect to *L*,

$$L = \frac{B}{2\sin(\beta)}. \tag{5.8}$$

Force on *L* is equal to *L* times *R*,

$$F_L = LR = \frac{BR}{2\sin(\beta)}. \tag{5.9}$$

By use of Newton's second law it is possible to find $R_{Crushing}$. Figure 5.4 shows which forces that are acting on the bow.

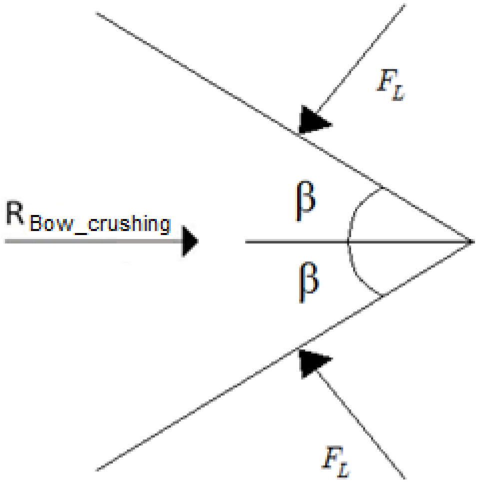


Figure 5.4 $R_{crushing}$ balances the crushing force from ice

Newton's second law states that the sum of the forces in x-direction is equal to zero,

$$\sum F_x = R_{Bow\_crushing} - 2F_L \sin(\beta) = 0 \,. \tag{5.10}$$

Inserting for $F_L$ from equation (5.9) and solving equation (5.10) for $R_{crushing}$ gives

$$R_{Bow\_crushing} = 2\frac{BR\sin(\beta)}{2\sin(\beta)} = BR \,. \tag{5.11}$$

### 5.3.2 Frictional resistance in bow, $R_{Bow\_friction}$

Frictional resistance in the bow appears when ice is scraping along the bow. The direction of the frictional force is always tangential to the bow. It is therefore necessary to investigate a curved bow, see Figure 5.5.

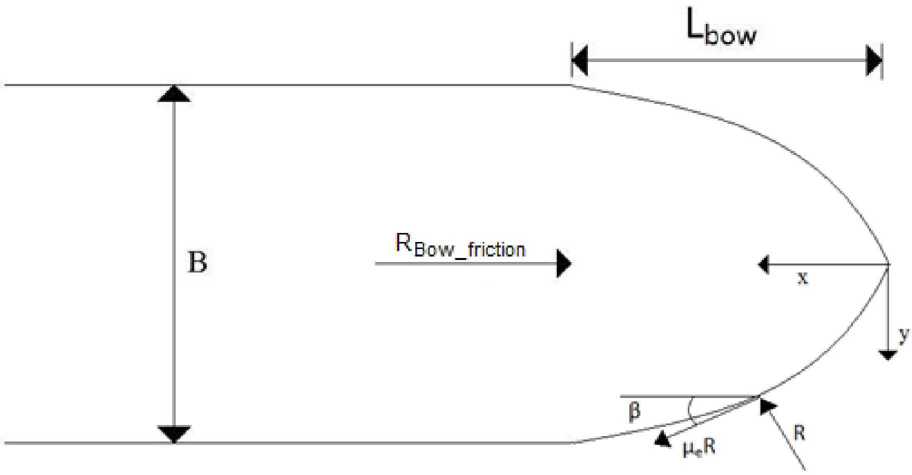


Figure 5.5 A vessel pushing through an ice ridge, showing the frictional forces on the bow

The tangential friction force in each point at the bow is given by

$$f = \mu_e R L_{force}, \tag{5.12}$$

where $L_{force}$ is the length which the friction force is acting on.

By dividing the bow into strip element with length *ds*, and by use of geometry this means that the friction force in each strip element is given by

$$df = \mu_e R ds. \tag{5.13}$$

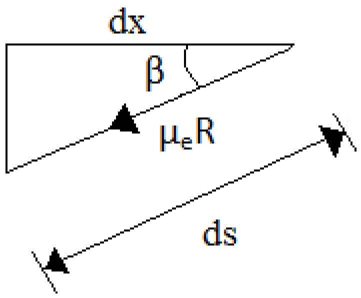


Figure 5.6 Illustrates simple geometry

By studying Figure 5.6 the formula

$$\cos(\beta) = \frac{dx}{ds} \tag{5.14}$$

can be established, which solved for *ds* and inserted into equation (5.13) gives

$$df = \frac{\mu_e R dx}{\cos(\beta)}. \tag{5.15}$$

And finally by integrating over the whole bow length in x-direction, the friction,

$$f = \int_0^{L_{bow}} \frac{\mu_e R}{\cos(\beta)} dx = \frac{\mu_e R L_{bow}}{\cos(\beta)}, \tag{5.16}$$

can be found.

With the use of Newton's second law it is now possible to find $R_{friction}$, Illustrated by Figure 5.7.

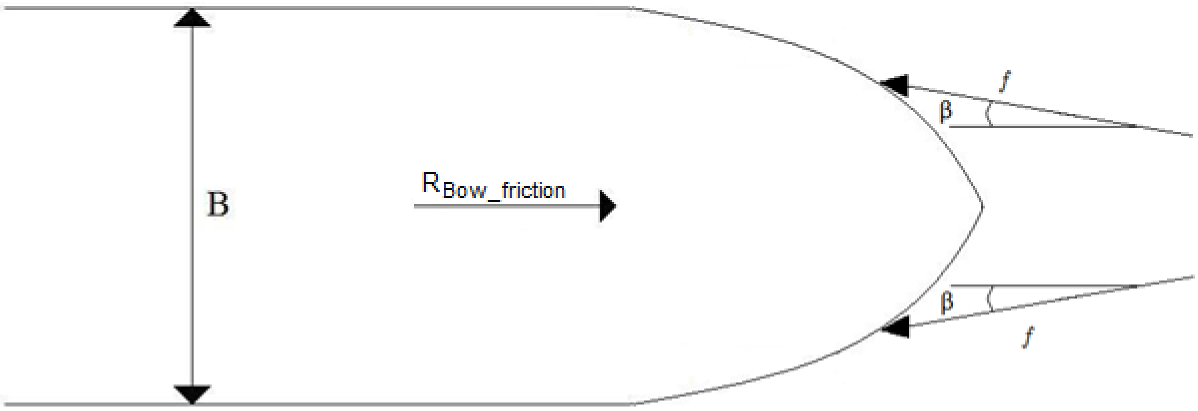


Figure 5.7 $R_{friction}$ has to balance the frictional forces from the ice on the bow

$$\sum F_x = R_{Bow\_friction} - 2f\cos(\beta) = 0\,. \tag{5.17}$$

Inserting for friction, *f* and solving for $R_{friction}$ gives

$$R_{Bow\_friction} = \frac{2\mu_e R L_{bow}\cos(\beta)}{\cos(\beta)} = 2\mu_e R L_{bow}\,. \tag{5.18}$$

Now, when both the crushing and friction resistance in the bow are calculated, a formula for total resistance in the bow can be established with combining equation (5.11) and (5.18),

$$R_{Bow} = R_{Bow\_crushing} + R_{Bow\_friction} = BR + 2\mu_e L_{bow} R\,. \tag{5.19}$$

## 5.4 Mid body resistance, $R_{Midbody}$

In mid body the resistance is assumed to consist of only friction, and equation (2.1) simply reduces to

$$R_{Midbody} = R_{Midbody\_friction}, \tag{5.20}$$

where $R_{Midbody\_friction}$ is, as the name indicate, the friction on the mid body due to contact with ice

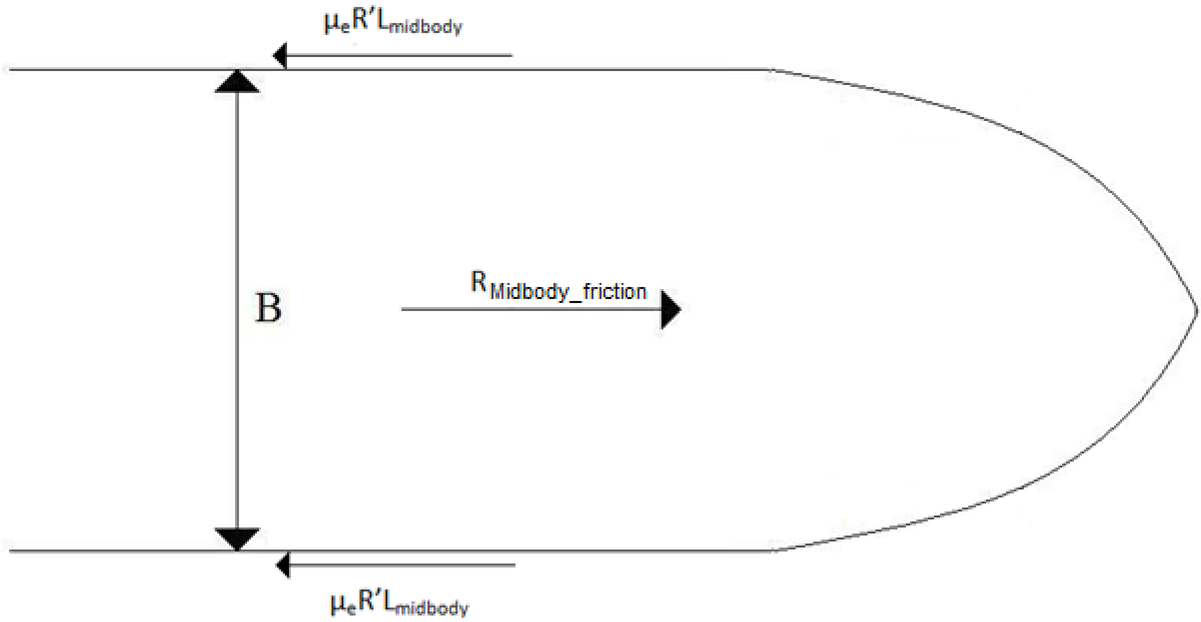


Figure 5.8 $R_{Midbody\_friction}$ has to balance the frictional forces from the ice on the mid body

As for the bow friction, the mid body friction is tangential to the vessel. Hence the mid body friction is acting on the vessel is in the opposite direction of motion. Therefore as the Figure 5.8 illustrates, Newton's second law can be used, and gives

$$R_{Midbody\_friction} = 2\mu_e R' L_{midbody}. \tag{5.21}$$

For the situation where the vessel's mid body is longer than the ridge, the maximum mid body length which is in contact with ice is equal to the length of the ridge, $L_{ridge}$. In this case the formula for the mid body friction becomes

$$R_{Midbody\_friction} = 2\mu_e R' L_{ridge}, \tag{5.22}$$

where *R'* is the force per unit width. There is several way to determine the relationship between *R'* and *R*. One way is to assume that *R'* has a linear relationship with *R*, namely

$$R' = NR. \tag{5.23}$$

Formula (5.23) inserted into formula (5.21) gives

$$R_{Midbody\_friction} = 2\mu_e RNL_{midbody}. \tag{5.24}$$

The mid body resistance does as mentioned consists of friction only, such that

$$R_{Midbody} = R_{Midbody\_friction} = 2\mu_e RNL_{midbody} \quad (5.25)$$

Mellor (1980) suggest the value of *N* should be in the range 0.06 to 0.13 for brash ice, however for the case of an ice ridge Kaj Riska has proposed a higher value. This report assumes *N* equal 0.5. In this report *N* is primary going to be a constant value. Another way to calculate *N*, is to define active and passive stress. Ice do also tend to gather up around the hull, to take this into account the relationship between the height of disturbed or gathered ice, *h2*, and undisturbed ice, *h1,* has to be accounted for. From Mellor (1980) is

$$N = \frac{h2}{h1}\frac{K_A}{K_P}, \quad (5.26)$$

where $K_A$ and $K_p$ are active and passive stress, defined as;

$$K_A = \frac{1-\sin(\phi)}{1+\sin(\phi)}, \quad (5.27)$$

$$K_P = \frac{1+\sin(\phi)}{1-\sin(\phi)}, \quad (5.28)$$

where $\phi$ is the internal friction angle which is going to be discussed later.

## 5.5 Level ice resistance

As ice ridges often are frozen into level ice, the need for a way to calculate the resistance from level ice arose. The level ice resistance can be split up into four parts, namely breaking, submersion, crushing and velocity dependent resistance. By superposition the equation for the total level ice resistance becomes

$$R_{LI} = R_{LI_b} + R_{LIc}(t) + R_{LI_s} + R_{LI_v}(v), \quad (5.29)$$

where $R_{LI}$ is the total level is resistance. $R_{LI_b}$, $R_{LIc}(t)$ and $R_{LI_s}$ represent the level ice resistance due to breaking, submersion and crushing . $R_{LI_v}(v)$ is the velocity dependent level ice resistance.

The level ice resistance will in this thesis be based on level ice resistance from Eskil Røset master thesis (Røset 2009, NTNU) with a simplification. The simplification is on the crushing part of the resistance, which in Røset's master is varying periodically with time and degree of penetration. In this thesis the crushing part will be consider constant. This simplification is done in order to reduce the simulation time; varying crushing resistance would slow down the process. Another justification for the simplification is that the crushing resistance is only one of four contributors to the total level ice resistance. Already, there is relative high uncertainty in this calculation due to variations in ice properties. These acknowledgements all defend a decision to neglect the variations in level ice crushing resistance.

By taking the simplification into account, RLIc(t) becomes RLIc and  the total ice resistance can be written as

$$R_{LI} = R_{LI_b} + R_{LIc} + R_{LI_s} + R_{LI_v}(v)\,. \tag{5.30}$$

Expressions for the different resistance contributions in equation (5.30) are found from Lindquist's formulas from 1989,

$$R_{LI_b} = 0.003\sigma_f B h_{li}^{1.5}\left(\tan\upsilon + \mu\frac{\cos\alpha}{\sin\beta'\cos\upsilon}\right)\left(1+\frac{1}{\cos\upsilon}\right), \tag{5.31}$$

where

$$\upsilon = \tan^{-1}\left(\frac{\tan\alpha}{\sin\beta'}\right), \tag{5.32}$$

$$R_{LIc} = 0.5\sigma_f h_{li}^{\;2}\,\frac{\tan\alpha + \mu\dfrac{\cos\alpha}{\cos\upsilon}}{1-\mu\dfrac{\sin\alpha}{\cos\upsilon}}, \tag{5.33}$$

$$R_{LIs} = \delta_\rho g h_{li} B[T_d\frac{B+T_d}{B+2T_d} + \mu(0.7L - \frac{T_d}{\tan\alpha} - \frac{B}{4\tan\beta'} + T_d\cos\alpha\cos\upsilon\sqrt{\frac{1}{\sin\alpha^2}+\frac{1}{\tan\beta'^2}})], \tag{5.34}$$

$$R_{LIv}(v) = \left(\frac{1.4R_{LI_c}}{\sqrt{gh_{li}}} + \frac{1.4R_{LI_b}}{\sqrt{gh_{li}}} + \frac{9.4R_{LI_s}}{\sqrt{gL}}\right)v_{rel}\,. \tag{5.35}$$

Lindquist's equations, equation (5.31)-(5.35), contains numerous new and already introduced variables. These variables are explained in the table below. For numerical values, see Appendix.

| Variable | Physical explanation |
|---|---|
| $\sigma_f$ | Flexural strength of the ice |
| $B$ | Vessel breadth |
| $h_{li}$ | Ice thickness |
| $\alpha$ | Stem angle |
| $\beta'$ | Waterline angle |
| $\mu$ | Friction coefficient |
| $\delta_\rho$ | Difference between water and ice density |
| $g$ | Gravitational acceleration |
| $T_d$ | Vessel draught |

Table 5.1 Explanation of variables used in level ice calculation

## 5.6 Total resistance

The total resistance is a sum of bow resistance and the mid body resistance, which is found by adding equation for the bow resistance, (5.19) and the mid body resistance (5.25),

$$R_{total} = R_{Bow} + R_{Midbody} = BR + 2\mu_e L_{bow} R + 2\mu_e RNL_{midbody} \,. \tag{5.36}$$

Note that when level ice is present, the level ice resistance from equation (5.30) does also need to be added into the total resistance.

It is possible to rewrite the expression so that the total resistance is a function of the waterline angle instead of either the breadth of the vessel or the length of the bow. This however seems unnecessary, assuming that the characteristics of the vessel are known.

## 5.7 Resistance distribution

When a vessel is penetrating an ice ridge the total ice resistance will not be constant over time. The total resistance at a time instant will be decided by the vessels position relative to the ice ridge. For instants: initially after a vessel-ice ridge impact the only contribution to ice resistance is the bow resistance, and after the vessel bow has penetrated the ice ridge there will only be a mid body resistance. It is convenient to divide the distribution into four stages, depending on how much of the vessel that has penetrated the ice. Note that level ice is not considered in this section as the level ice resistance only varies with ice thickness and relative ice-vessel velocity.

### 5.7.1 The four stages of ridge penetration

**Stage 1:** Describes the situation where only the bow has penetrated the ice ridge. Hence, only the bow resistance will be a contributor to the total resistance. In the end of this stage bow resistance will experience its peak value, which corresponds to the bow resistance calculated by Mellor's formula.

**Stage 2:** At this stage both the mid body and the bow is in contact with ice. The bow resistance will start to decrease, whereas the mid body resistance is increasing. Due to larger decrease in bow resistance then increase in the mid body resistance the total resistance will experience a total net decrease at this stage.

**Stage 3:** The ice ridge has passed the bow, and only the mid body is in contact with ice. There is no change in the area that is in contact with ice; hence the total resistance will be constant at this stage.

**Stage 4**: The vessel is leaving the penetrated ridge, and the mid body resistance start to decay. In the end of stage 4 the vessel has left the ice ridge and the ice ridge resistance is zero.

### 5.7.2 Superposition of bow and mid body resistance

The bow resistance is assumed to grow exponentially from zero to the calculated max at the first stage, and thereafter decreases exponentially back to zero at the second stage, see Figure 5.9 below

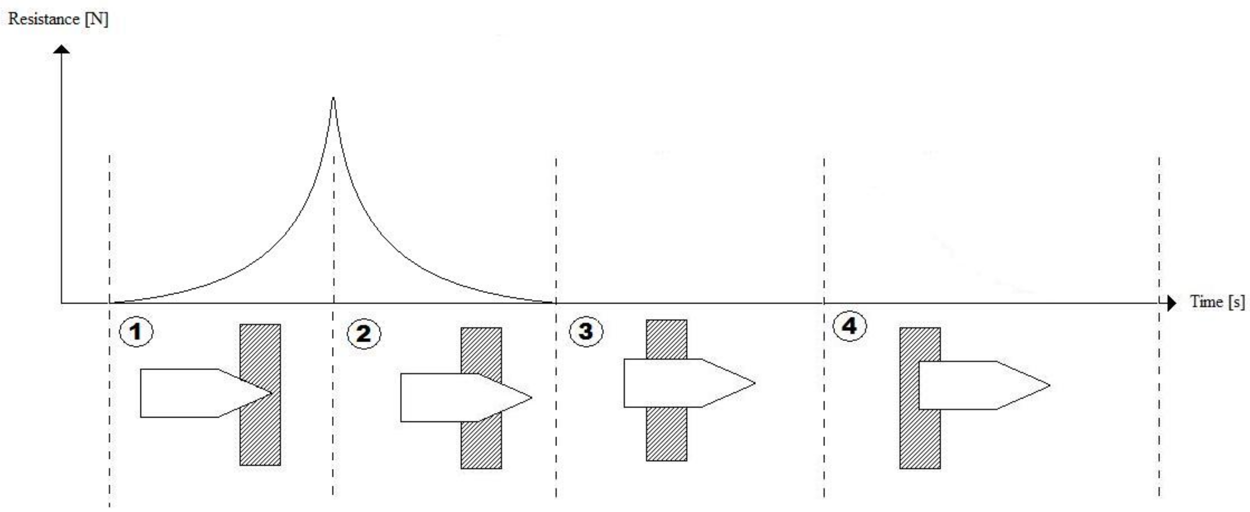


Figure 5.9 Bow resistance in different stages

The mid body resistance is assumed to go from zero at the start of stage 2 up to the max value at the end of stage 2 following a s-shape. The max value is sustained the whole 3rd stage. At 4th stage the resistance decreases from maximum value to zero following an inverse s-shape as illustrated in Figure 5.10.

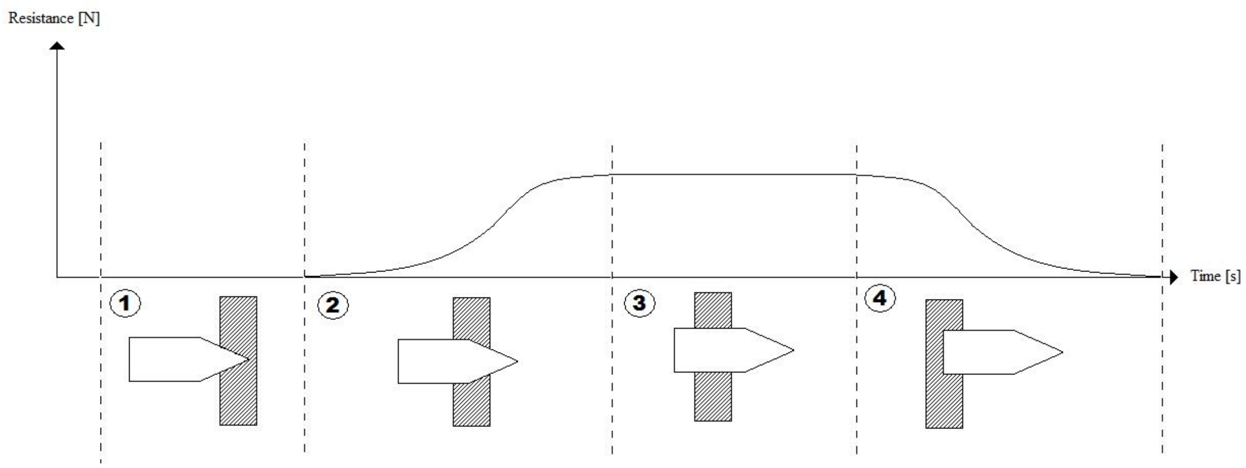


Figure 5.10 Mid body resistance in different stages

The whole picture is obtained by adding the bow and mid body resistance at each stage. This creates the total resistance over all the stages as showed in Figure 5.11.

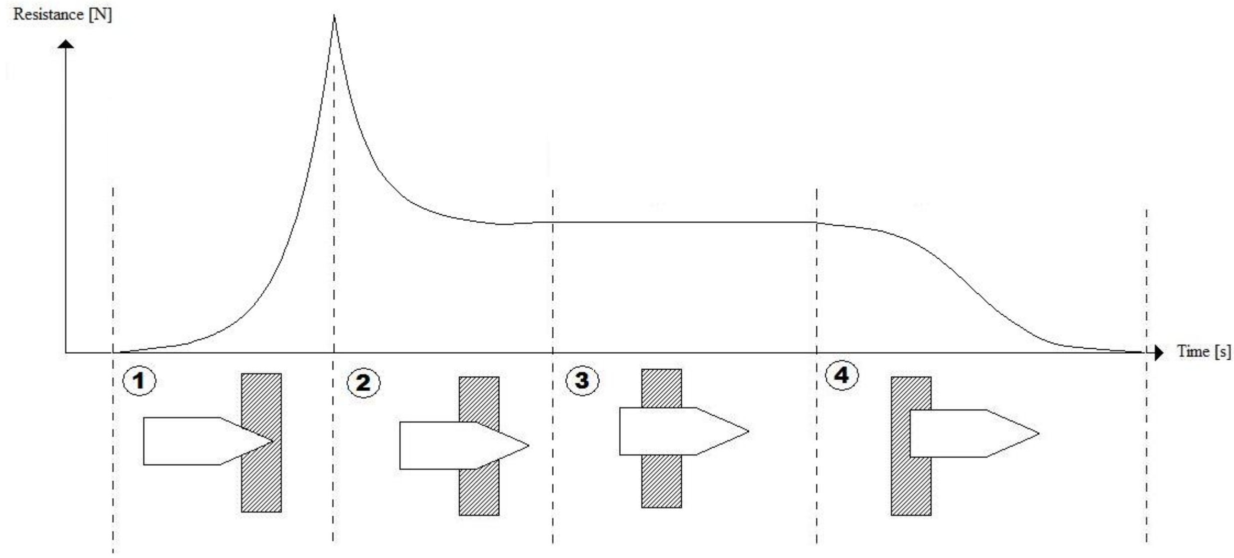


Figure 5.11 The sum of bow resistance and mid body resistance in each stage

## 5.8 Discussion of method B

Method B gives the opportunity to change the vessel and ice ridge characteristics, which provides more flexibility than method A. Dividing the resistance into several terms also gives the possibility to investigate how different changes in the parameters values affects the specific parts of the resistance distribution. The method is relative simple in terms of calculation for each time step. This means that a computer can calculate the results real time or even faster.

A drawback is the fact that the method only calculates the resistance in the direction of motion. However there may be a way to extend this method, which will give an output of several degrees of freedom. The method certainly needs some adjustments before it can be fully integrated as a part of the MCSim.

Assumptions are made about how the graph develops, for both the bow resistance and mid body resistance. In the bow the resistance is assumed to grow exponential, this assumption is based upon the fact that bow resistance is a function of the ice thickness squared. For the mid body the resistance is assumed to follow a s-form, close to a inverse tangent function until the mid body is in contact with the whole length of the ice ridge. The mid body resistance has at that time reached its maximum. The maximum is extant until the ice ridge is exiting the mid body, where the opposite effect will take place.

# 6 The SIMULINK model

In order to get an overview over the SIMULINK model the use of flowcharts are useful. In this chapter, flowcharts illustrating the SIMULINK model will be presented. First a global overview will be presented, and then two main subsystems will be discussed.

## 6.1 Global overview

The SIMULINK model can be split into three parts; DP-system, Vessel dynamic and Ice loads, connected as shown below in Figure 6.1. The Ice loads will be discussed in detail in chapter 0 and the DP-system will be discussed in chapter 8. Additional to ice loads and control forces, the vessel dynamic will also experience environmental forces, like wind- wave- and current –forces. The vessel dynamic is already included in the MCSim project and will not be discussed in this chapter. The DP-system and ice loads are new contribution to the MCSim and will therefore be investigated in detail.

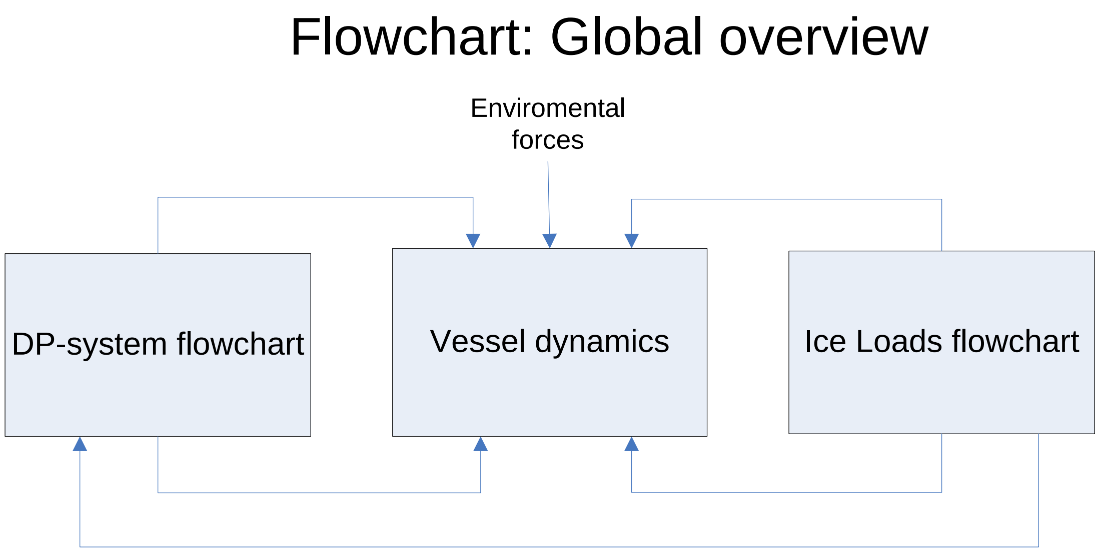


Figure 6.1 A flowchart, showing an overview of the system

## 6.2 Ice modeling

The “Ice loads” block gets input from vessel dynamic, namely vessel position, heading, velocity and heading rate. The Ice loads block uses the inputs to perform its main two objectives, namely to validate ice contact and to calculate ice resistance. If there is no ice contact, zero ice resistance is return to the vessel dynamics. After ice contact is confirmed, the ice ridge loads, and level ice loads are independently calculated. Finally the ice matrix, including ice position and shape is updated. The Ice loads block provides ice resistance to vessel dynamics. The block also gives a feed forward to the DP-system containing information about the ice position and velocity. For a simplified flowchart, see Figure 6.2. A more detailed description of the “Ice loads” block is found in chapter 0.

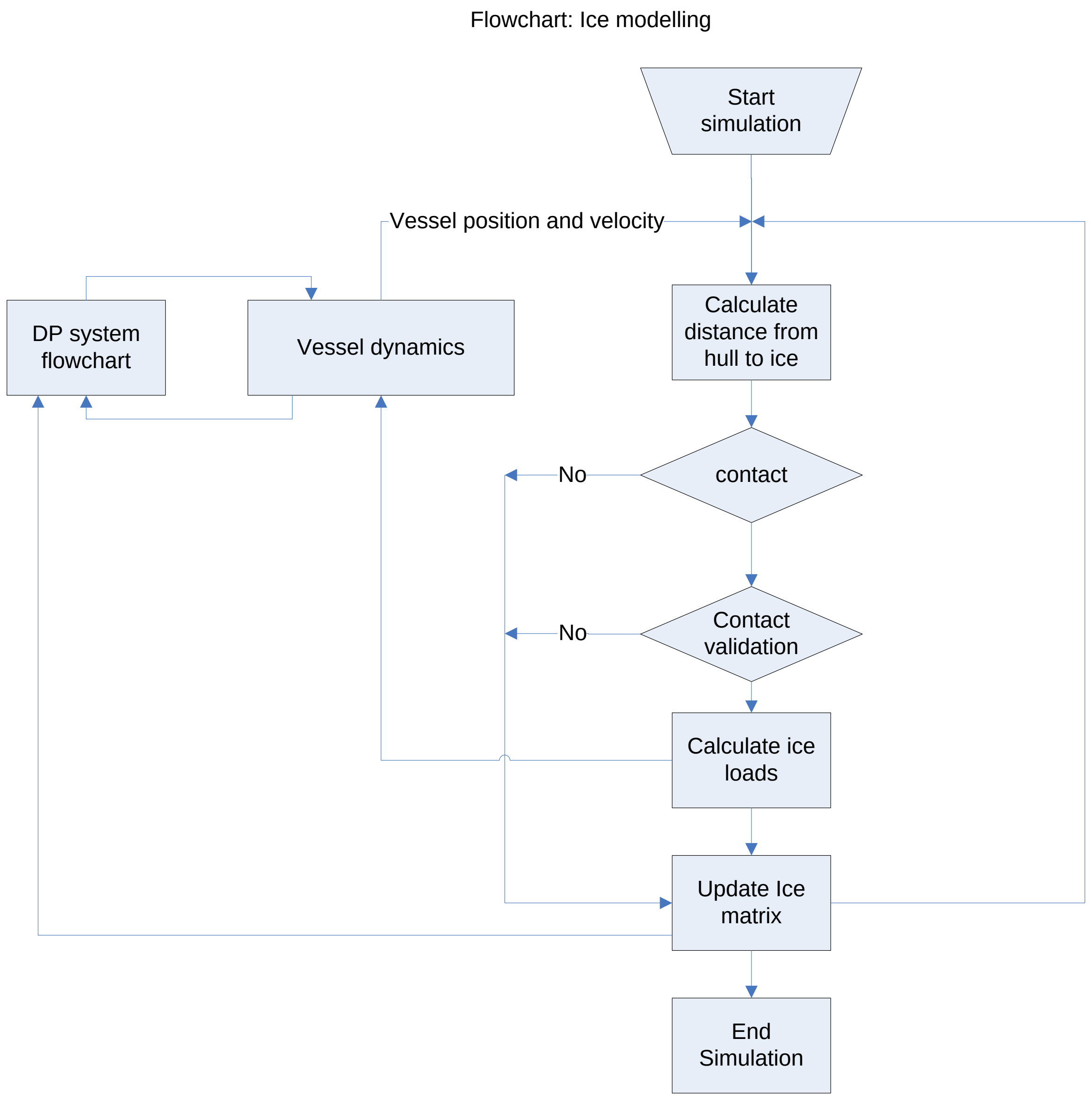


Figure 6.2 Flowchart showing the ice load calculations

A more direct presentation of the ice ridge model is presented in Figure 7.7.

## 6.3 DP - System

For the purpose of controlling the vessel a DP-system is used. By evaluating information regarding ice position and velocity, the specific DP-tactic creates a position set point to the reference model. The flowchart for this DP-system is presented in Figure 6.3. A more specific description of this system can be found in chapter 8.

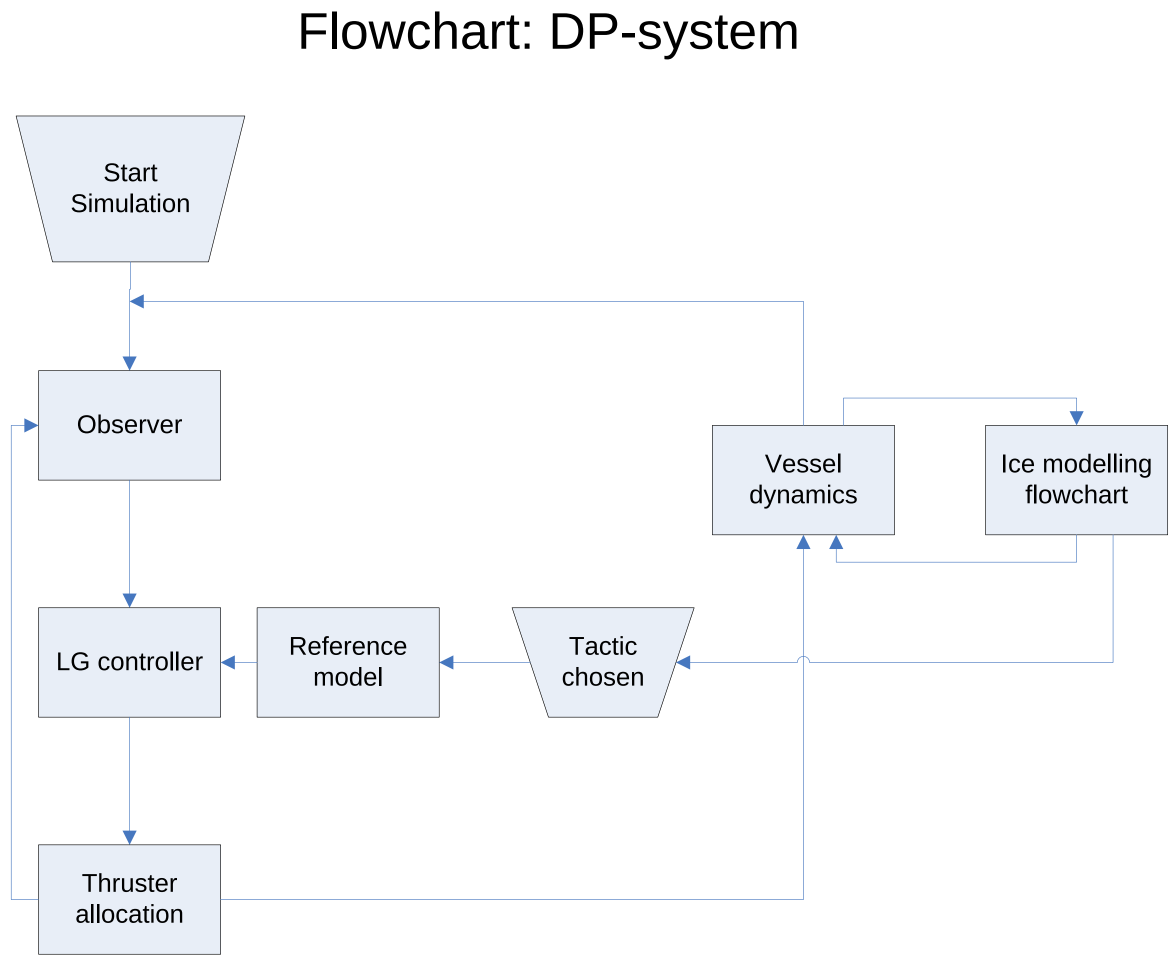


Figure 6.3 Flowchart showing the DP-system

# 7 Implementations of the "Ice loads" block

## 7.1 Implementation of ice ridge simulator

The basis for the simulations in this thesis is The Marine Cybernetics Simulator (MCSim). The MCSim consists of a library of MATLAB/SIMULINK blocks and scripts for a variety of marine vessel modeling and simulation purposes. The simulator is based on the freely available Marine Systems Simulator (MSS), but also includes modules and code only for use in research and education at the Norwegian University of Science and Technology (NTNU). MCSim is developed and continuously updated by students, professors and researchers at department of Marine Technology and department of Engineering Cybernetics, NTNU. More information of the MCSim can be found in "MCSim documentation, NTNU 2009".

In this thesis the ability to simulate the interaction between an ice ridge and a marine vessel is implemented through the "Ice Ridge Loads" block. The "Broken Ice Loads" (Petter Stuberg, 2009) and "Level Ice loads" (Eskil Røset, 2009) are created by previous students at the department of Marine Technology.

## 7.2 The simulation

The duration of the simulation is user specified, this means that the MCSim will only perform resistance calculations for a time period specified by the user. In order to describe an ice ridge interaction in a satisfactory way it is necessary to choose a simulation time large enough for MCSim to perform resistance calculations for all stages of a ridge penetration, from initial impact to complete penetration.

Depending on the needed mathematical accuracy, a suitable sampling interval has to be specified. The sampling interval should be chosen small enough to produce continuous results, but large enough to avoid unnecessarily high computational loads. The time between two sampling instants are called a time step.

## 7.3 Implementation of ice ridge block

In order to perform ice ridge simulations the inputs from MCSim must be adjusted and preset accordingly to the wanted simulation mode. For an ice ridge simulation the relevant inputs are the vessel size and the vessel velocity. The MCSim provide a vessel model with a preset size and a corresponding node representation. The nodes are represented in a matrix, namely the "vessel matrix", where every entry holds the value of one specific node coordinate. The "vessel matrix" is updated at each time step accordingly to the vessel velocity.

Vessel velocity and the environmental loads, wind and waves are adjustable parameter which is preset by the user before each simulation. The environmental parameters are not of interest for a pure ice resistance simulation and are in this thesis neglected in most of this thesis results. "Ice ridge velocity" and "Ice ridge length" are parameters introduced to the MCSim in this thesis. This allows the user to preset two additional parameters and hence expands the scope of a parameter analysis.

In order to understand the simulation of ice ridge loads four key contributors to the simulation must be explained.

- The ice matrix, a nodal representation of the ice ridge.
- Level ice loads, level ice loads experienced by the vessel.
- Degree of penetration, which gives an indication of ridge penetration at a certain time step.
- Maximum resistance, a maximum resistance value calculated based on ridge and vessel dimensions

**The ice matrix**

The ice ridge is separated into nodes in similar manner as the vessel. Each ice ridge node is represented by a coordinate in the ice matrix. For every time step the ice matrix is updated with new node coordinates accordingly to the preset ice ridge velocity. The ice matrix creates a basis for the ice ridge calculation. A contact validation process is done to confirm contact between ice ridge and vessel. No contact means zero ice loads, whereas contact confirmed starts calculation of ice loads. In order to gain more momentum when approaching an ice ridge, a feature making it possible to reverse the vessel when stuck in the ice is desirable. Therefore the ice matrix is updated such that also the shape of the ice ridge is changed, leaving already penetrated ice ridge to be open water when a repeated strike is preformed on the ice ridge. This kind of footprint in the ice is illustrated in Figure 7.1 to Figure 7.3. In these figures the vessel and ice matrix are illustrated in 2D, even though the matrices in the actual model are in 3D. Figure 7.1 simply illustrates the vessel - and ice –matrices before impact. In Figure 7.2 the vessel has managed to plough its way through some of the ice ridge, but are now stuck and need to reverse to gain momentum. Figure 7.3 shows that the vessel has made a “footprint” in the ice matrix, making it possible for the vessel to dig or eat itself through the ice ridge by revering when stuck. Note that even though the vessel leaves open water when reversing, mid body friction is still present.


Figure 7.1 Vessel matrix and ice matrix before impact

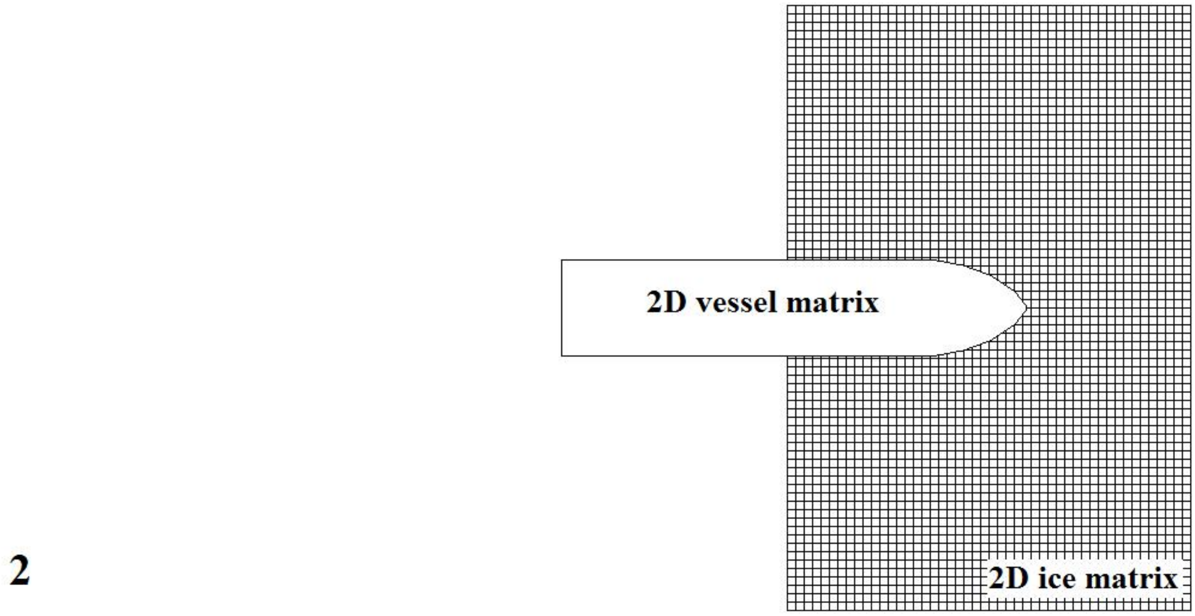


Figure 7.2 Vessel is stuck in the ice ridge, and have to reverse to gain momentum

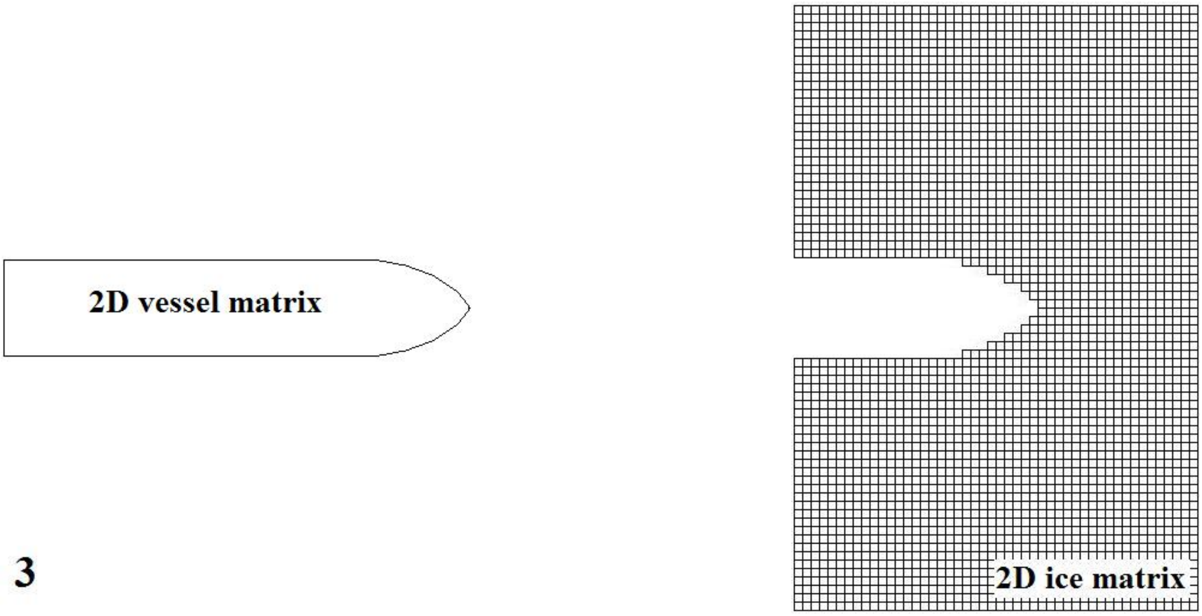


Figure 7.3 The vessel has created a "footprint" in the ice ridge and therefore also in the ice matrix

A more realistic picture of a footprint will include some fragmentation of the sides in the footprint as well as some broken ice inside the footprint, see Figure 7.4. However, as most of the broken ice will be pushed to the sides when the vessel reenters, it is assumed that the situation in Figure 7.3 is valid.

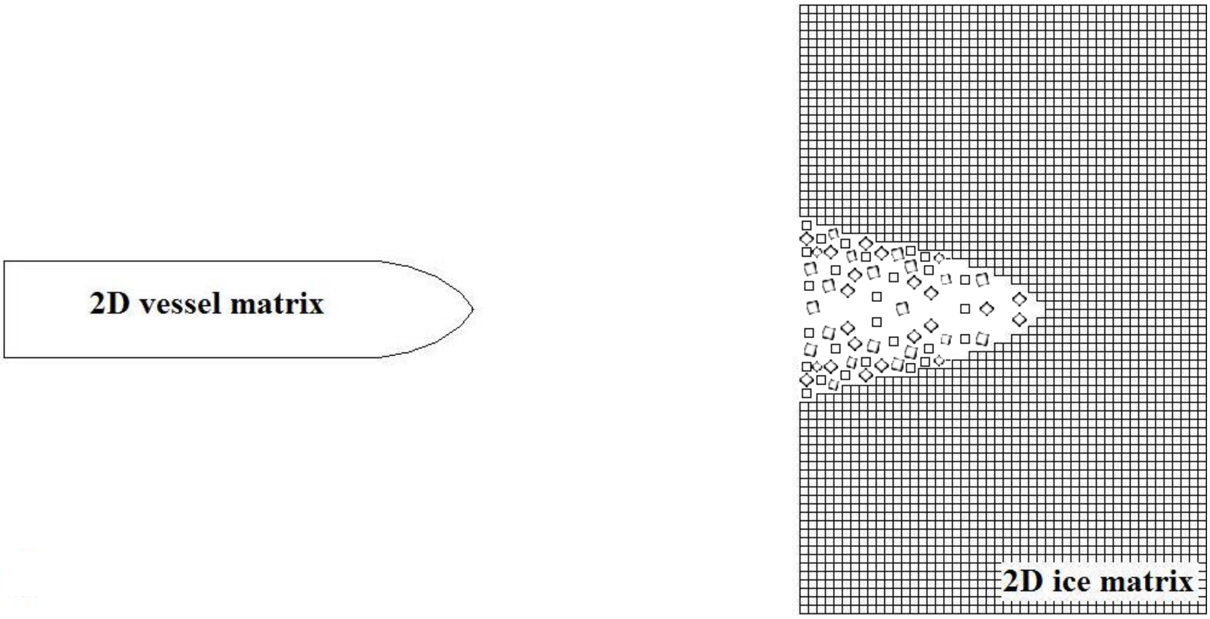

Figure 7.4 A more realistic illustration of the footprint in the ice matrix

**Level ice loads**

Ice ridges are often found frozen into level ice. This, combined with the fact that the consolidating layer in an ice ridge can modeled as level ice, made it necessary to make a velocity dependent level ice resistance. A simplified ice ridge model is illustrated in Figure 7.5. The consolidating layer is typically 1.8 times the level ice, as proposed by Kaj Riska. Due to that much of the level ice loads are a function of the thickness squared; the level ice load is an important part of the total ice ridge loads. The level ice loads are based on the same formulas as in Røset's, master thesis about level ice (Eskil Røset 2009), but with simplifications for faster calculations as discussed in chapter 0. As for the ice ridge, contact is to be validated prior to calculation.

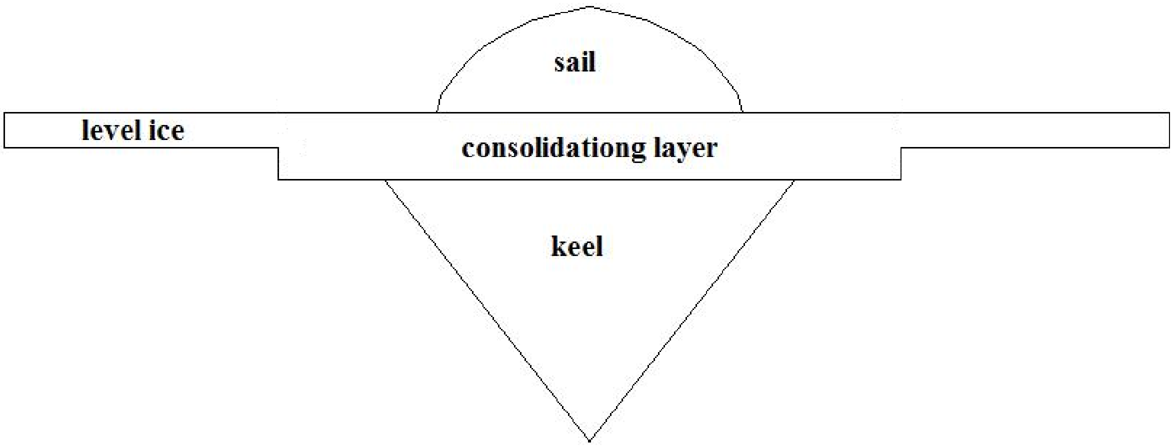

Figure 7.5 Showing that consolidating layer can be approximated as thick level ice

**Degree of penetration**

The degree of penetration depends on the interaction between the ice ridge and the vessel. Before ridge and vessel contact is established the degree of penetration will hold the value zero. In order to determine whether contact between ridge and vessel is established the entries of the Ice matrix are compared to the ones of the "vessel matrix". Subsequent to the established contact the degree of penetration will hold a value equal to the distance of ridge penetration, see Figure 7.6, where the degree of penetration are symbolized by *delta*.

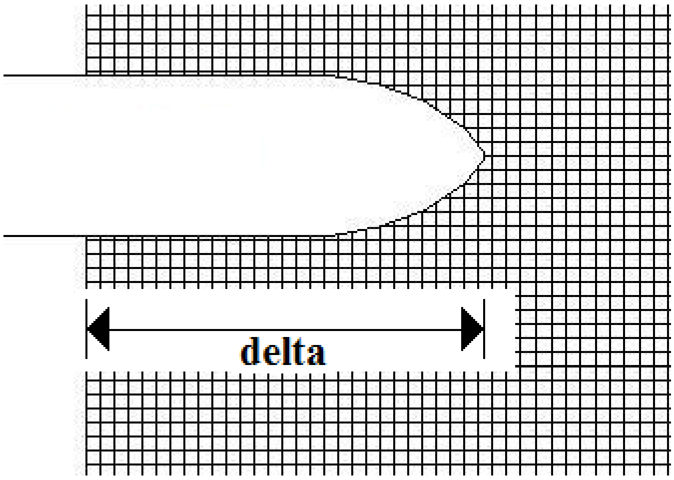


Figure 7.6 Degree of penetration, here symbolized by delta

**Maximum resistance**

Ice ridge resistances are calculated for the bow and mid body section of the vessel by use of formula proposed by Mellor (1980) as shown in chapter 0. These formulas provide a maximum value for bow and mid body resistance. The maximum values will vary with the size of the ice ridge and the geometrical shape and size of the vessel. By use of the "degree of penetration" variable and the maximum values for ridge resistance the ice ridge simulator will distribute the resistance forces according to the theory in chapter 5.7, from initial impact between ridge and vessel to full penetration.

Results of the performed simulations are presented for a vessel using customary DP in chapter 0, and with tactics in chapter 11.

Figure 7.7 illustrates which calculations that are carry out inside the “Ice Ridge load” block. Note that the name “Ice ridge loads” can be misleading, knowing that the block also is capable of handling level ice loads.

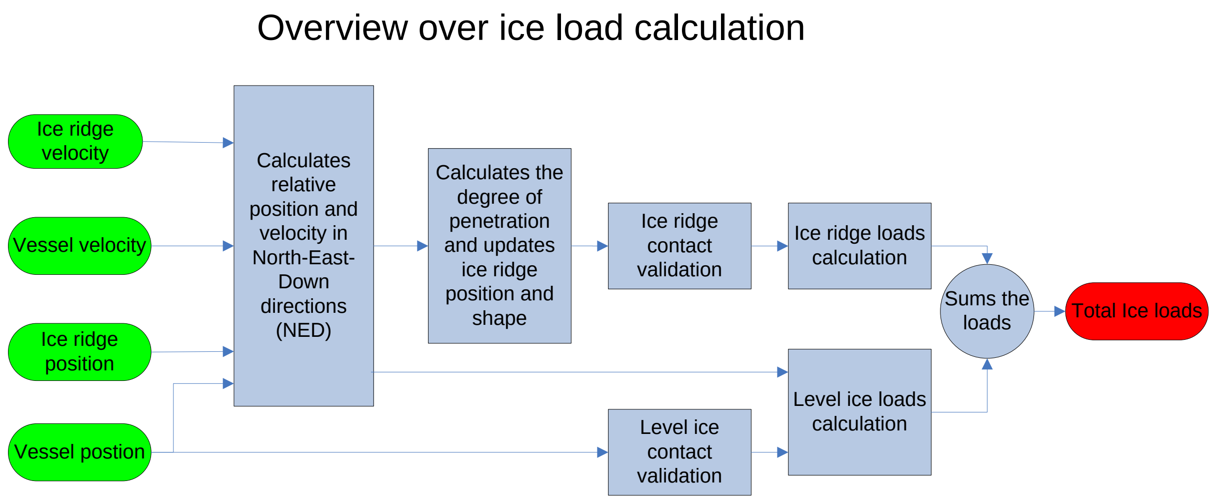


Figure 7.7 The "ice loads" block

As shown in Figure 7.7 the total ice load is a combination of both ice ridge loads and level ice loads. The ice ridge loads and the level ice loads are calculated independently according to theory in chapter 0.

# 8 Implementation of the DP control system

## 8.1 Introduction

The aim of this thesis has been to create a DP-controller suitable for different ice regimes. To verify that the DP-controller has the desired qualities it will be implemented in a simulator. The simulator used in this master thesis is the MCSim-toolbox which includes a mathematical model of a marine vessel and its dynamics. The MCSim-toolbox allows the possibility of introducing external forces like current, wind and waves. By introducing ice loads and DP-controller to the MCSim-toolbox it is possible to perform complete simulation of a vessel on DP, affected by wind, wave, current and ice forces.

## 8.2 The DP-system

In this chapter a suggestion for a DP control system suited for station keeping and ice navigation is presented.  The DP controller presented is expected to function in level ice, broken ice, ice ridge and open water. In chapter 0 a complete control system that will detect an incoming ice load and predict and execute “the best strategy” for ridge penetration will be introduced. “The best strategy” varies for the different modes of operations and will be discussed subsequently.

The DP control systems is implemented in the MCSim-toolbox and tuned to handle the wind, wave and current forces in addition to the external ice loads from level ice, broken ice, ice ridge or a combination of them.

In order to investigate the vessel behavior in the case of interaction with different ice regimes thruster forces and ice loads are introduced to the MCSim-toolbox. It is assumed that the superposition principle is valid and that there is no coupling between the ice loads and the surrounding environment. This is illustrated in Figure 8.1, which shows how the “DP-Controller” and “Ice Loads” rely on input in terms of vessel position and velocity, and how the information is used to produce forces that again are used in the “Vessel dynamics”-block.

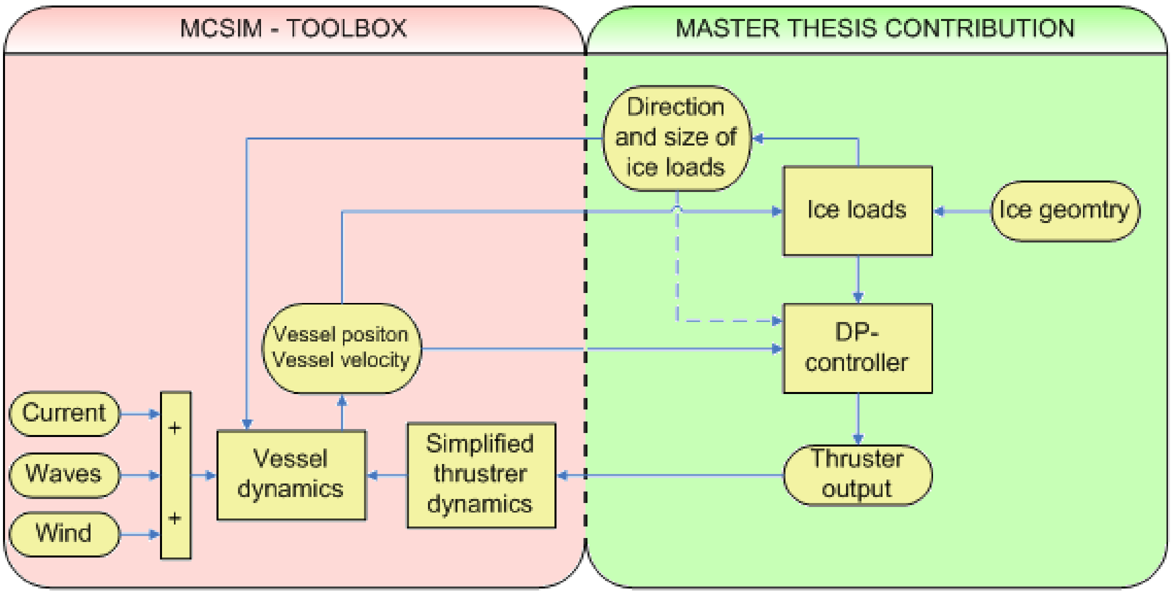


Figure 8.1 Flow diagram of the DP-controller

## 8.3 DP-Controller

The objective of a DP-controller is station keeping and maneuvering of a vessel. For this thesis the objective is driving the desired states to zero, i.e. the errors given by,

$$\tilde{\eta} = \hat{\eta} - \eta_d \ , \tag{8.1}$$

$$\tilde{\nu} = \hat{\nu} - \nu_d \ . \tag{8.2}$$

Respectively $\tilde{\eta}$ and $\tilde{\nu}$ are the deviation between measured and desired vessel position and between measured and desired vessel velocity.

The controller proposed for this thesis is a 3 DOF controller. The controller calculates general forces in surge and sway and a moment in yaw. The desired control law is on the form

$$\tau_c = -K_d \tilde{\nu} - R^T(\psi) K_p \tilde{\eta} - K_i \int R^T(\psi) \tilde{\eta} \ . \tag{8.3}$$

In the control law above $\tau_c$ represents the total control force, $R^T(\psi)$ is a transposed rotational matrix transforming from a north-east-down frame to body frame, while $K_d$ , $K_p$ and $K_i$ are the respective gain-matrices for derivate, proportional and integral action.

## 8.4 Linear quadratic optimal control

Linear quadratic regulation (LQR) is a way to automatically decide appropriate controller gains by solving a mathematical expression. This means that the settings gains are found by using a mathematical algorithm that minimizes a cost function with weighting factors supplied by a controller-developer. The algorithm calculates the controller gains that minimize the undesired deviations. In this master thesis the undesired deviations are position, heading and velocity. The main challenge with the LQR method is to provide reasonable weighting matrices which can be seen as an iterative process.

The optimal feedback, $\tau_{LQ}$ can be found by minimizing the cost function given by

$$J = \min_{\tau_{LQ}} \left\{ \frac{1}{2} \int_0^T (\tilde{x}_a^T Q_a \tilde{x}_a + \tau_{LQ}^T R \tau_{LQ}) d\tau \right\} \quad (8.4)$$

$R = R^T > 0$ and $Q_a = Q_a^T$ are cost matrices that must be specified for each case and determines the performance of the controller. $R$ is the control weighting matrix and Q a weighting matrix that penalize deviation from the desired states. $\tilde{x}_a$ is the augmented state error vector. The feedback control law that minimizes the value of the cost function (8.4) is $\tau_{LQ} = -G\tilde{x}_a$ where $G$ is given by the steady-state solution (Athans and Falb 1966). By solving the Algebraic Ricatti Equation

$$P_\infty A + A^T P_\infty - P_\infty B R^{-1} B^T P_\infty + C^T Q C = 0 \quad (8.5)$$

the steady state solution becomes

$$\tau_{LQ} = -R^{-1} B_a^T P_\infty \tilde{x}_a = G\tilde{x}_a, \quad (8.6)$$

where G is the control gain matrix.

## 8.5 Thruster allocation

Thruster allocation is a necessary part of the DP-system. It used for translating the need for thrust in surge, sway and yaw (and possible other directions) into physical feasible thrust on each engine. To manage this translation a satisfactory way, for each thruster it has to take into account; where on the vessel the thruster are placed, the cost of operating the thruster and the maximum capability of the thruster.

Thrust allocation involves computing the thruster inputs $u_i$ and azimuth angles. The inputs can be found from

$$\tau_c = \mathbf{T} f \quad , \tag{8.7}$$

$$f = \mathbf{K} u \quad . \tag{8.8}$$

*f* is the thrust vector for a given controller command, $\tau_c$. $\mathbf{K}$ is a scaling matrix chosen such that *u* varies from -100 to 100 percent. $\mathbf{T}$ is the thrust configuration matrix which describes which factor of its delivered thrust that is transmitted in each direction.

Assuming that there is no saturation, and knowing that angles are constant, this result in the generalized inverse (Fossen, 2002),

$$u = \mathbf{K}^{-1}\mathbf{T}^{\dagger}\tau_c, \quad , \tag{8.9}$$

$$\mathbf{T}^{\dagger} = \mathbf{W}^{-1}\mathbf{T}^{T}[\mathbf{T}\mathbf{W}^{-1}\mathbf{T}^{T}]^{-1} \quad , \tag{8.10}$$

where $\mathbf{W} = \mathbf{W}^{T} > 0$ is a positive definite weighting matrix, usually chosen to be diagonal. $\mathbf{W}$ should be selected so that using the less expensive thrusters is prioritized.

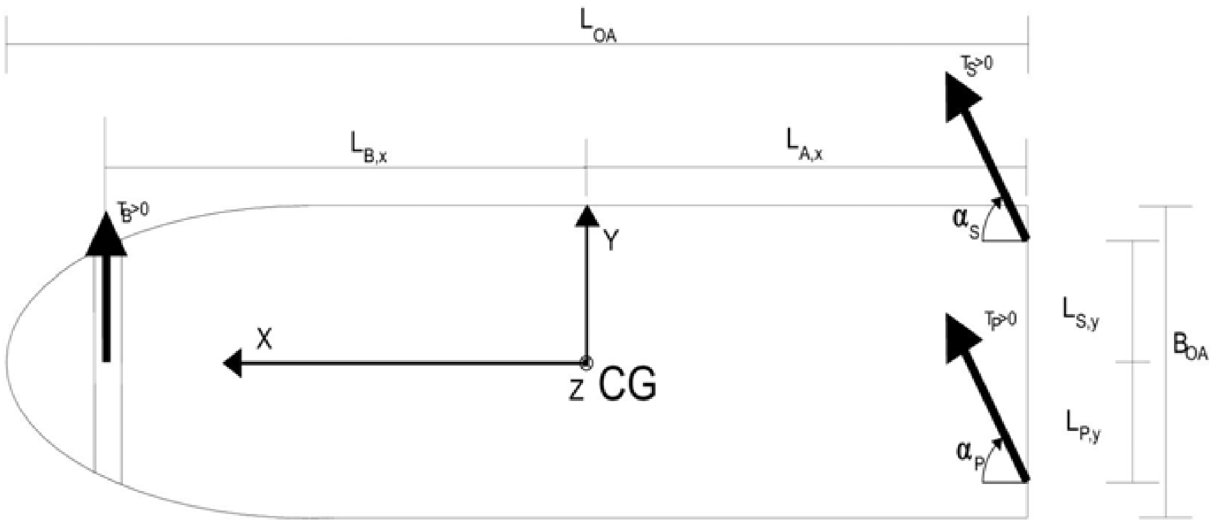


**Figure 8.2 Thruster configuration**

Figure 8.2 shows an example of a thruster configuration of a vessel. From this the thruster configuration the following thruster configuration matrix can be constructed.

$$\mathbf{T} = \left[ \begin{array}{c:c:c} 0 & \cos(\alpha_s) & \cos(\alpha_p) \\ 1 & \sin(\alpha_s) & \sin(\alpha_p) \\ \underbrace{L_{B,x}}_{\text{Bow Thruster}} & \underbrace{-L_{A,x}\sin(\alpha_s) - L_{S,y}\cos(\alpha_s)}_{\text{Starboard Azimuth}} & \underbrace{-L_{A,x}\sin(\alpha_p) + L_{P,y}\cos(\alpha_p)}_{\text{Port Azimuth}} \end{array} \right] \tag{8.11}$$

## 8.6 Reference model

When a change of vessel position or heading is desired, a reference model has to be used. It is used to smooth the reference input to the DP-controller. In this manner the controller avoid being saturated and it is possible to limit both speed and acceleration. An approach with three integrators ensures that both the velocity and the acceleration of position and heading are smooth and bounded. This is the main motivation for choosing a 3rd order model.

A first order low-pass filter cascaded with a mass-damper-spring system creates this 3rd order model, and has the following transfer function in general (Fossen, 2002),

$$\frac{\eta_{d_i}}{r_i^n}(s) = \frac{\omega_{n_i}^2}{(1+T_{LF}s)(s^2+2\zeta_i\omega_{n_i}s+\omega_{n_i}^2)} \quad (i=1,2,3) \tag{8.12}$$

where $T_{LF} = 1/\omega_{n_i}$ is the low pass filter time constant, and $\omega_{n_i}$ is the natural frequency of the mass-damper-spring system. A block diagram of the reference generator is shown in Figure 8.3 where velocity and acceleration saturation elements are also included to prevent high velocity and acceleration reference signals. In the simulations, the velocity reference is limited to 2 [m/s], 1 [m/s] and 0.02 [rad/s] in surge, sway and yaw, respectively.

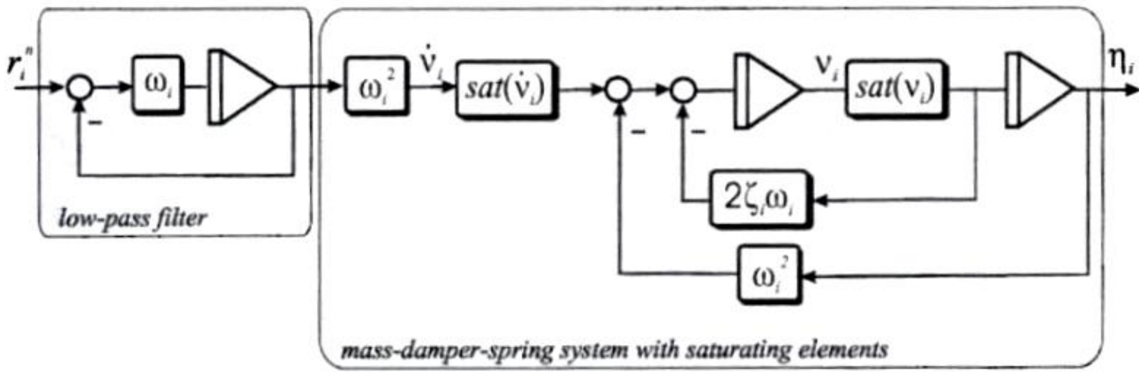


Figure 8.3 Reference model (Fossen, 2002)

The natural frequency of the system depends on the size of the step in desired position. The vessel can turn five degrees in a matter of seconds, but may need several minutes to turn 180 degrees. By specifying the $\omega_{n_i}$'s according to a simple rule that takes the desired reference position step into consideration, it can be made sure that the control system does not have too fast changes in reference position and velocity. The following reference time constants in surge, sway and yaw produces good reference signals for a wide range of position reference steps;

$$T_1 = 150 + 1.5|n_0 - n_r|, \tag{8.13}$$

$$T_2 = 150 + 1.5|e_0 - e_r|, \tag{8.14}$$

$$T_3 = 100 + 100|\psi_0 - \psi_r|. \tag{8.15}$$

# 9 Simulations of ice ridge loads with results and discussion

In this chapter, simulation results of a vessels navigating through an ice ridge will be presented and discussed. The chapter will focus on the ice ridge resistance according to formulas in chapter 0. It is presented by first showing a reference result with use of a set of default parameters. Thereafter one parameter at the time will be changed. The numerical values of the results have not been the focus of this thesis, since the comparable theory is limited. The influence on the resistance due to change of parameters will be illustrated and discussed in the following chapter. To help understand the behavior of the vessel better, a north-east map has been animated. The north-east map shows the vessel's position relative to a defined origin, see Figure 9.1. Of other analysis tools used, a simple north-east plot can be mentioned, which plots and logs the position of the vessel.

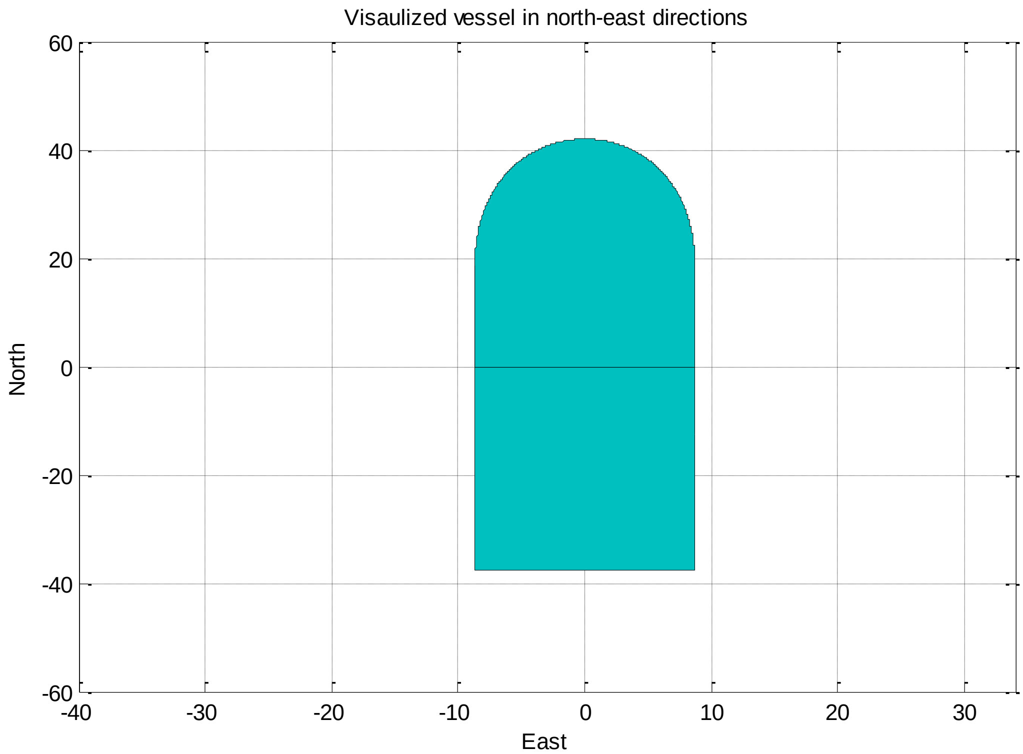


Figure 9.1 Visualized vessel in north-east directions

## 9.1 Establishing a basis for the resistance

By use of the formula (5.19) and (5.25), and the reference parameters, ref Appendix A for numerical values, the bow resistance and mid body resistance will obtain the shape as shown respectively in Figure 9.2 and Figure 9.3.

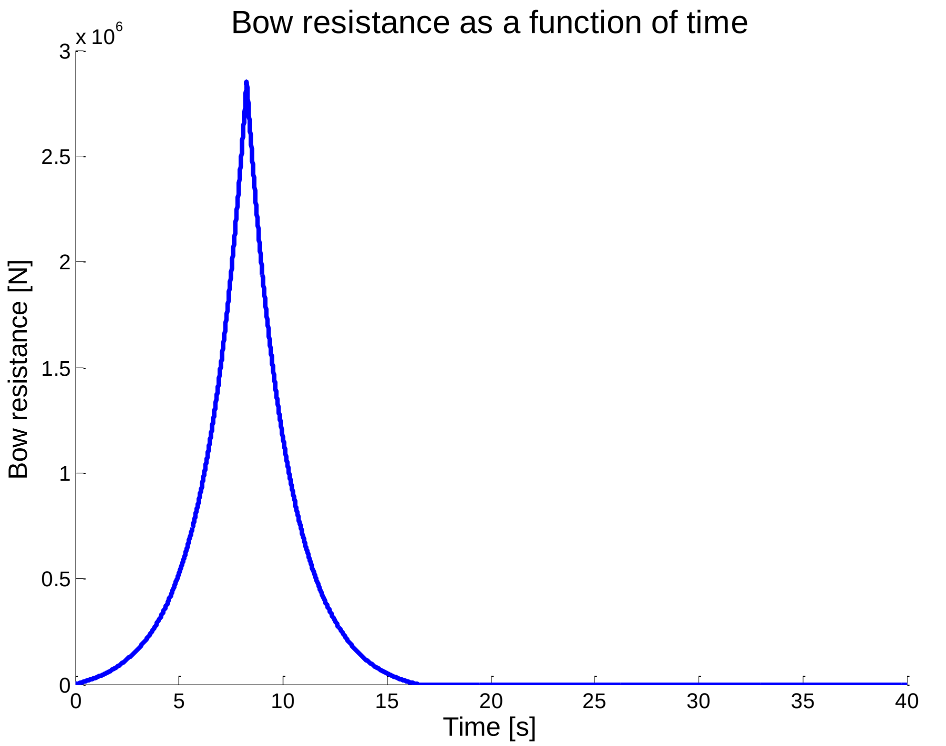


Figure 9.2 Bow resistance as a function of time

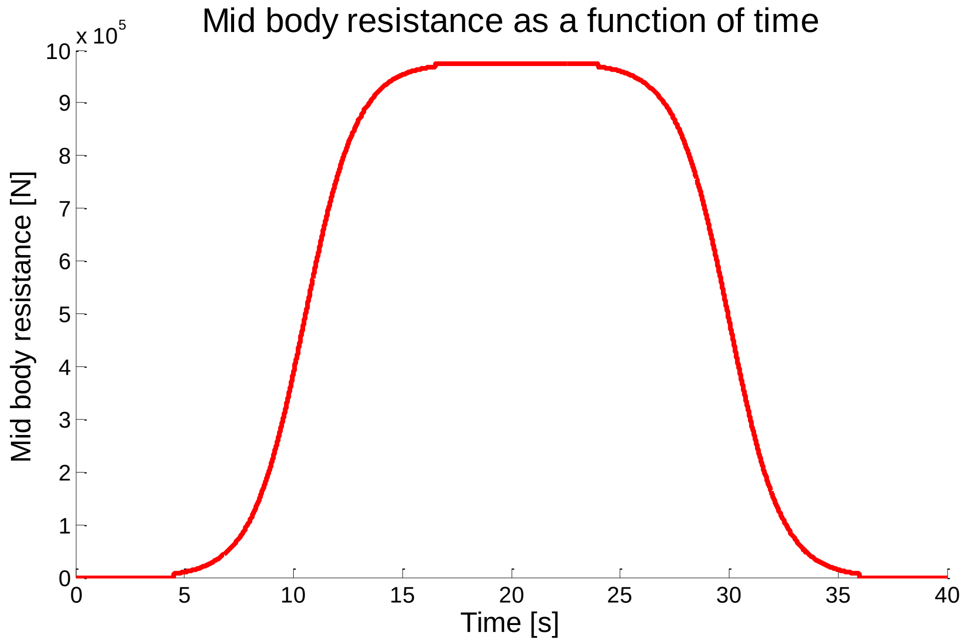


Figure 9.3 Mid body resistance as a function of time

The total resistance is found by adding the bow resistance and the mid body resistance at each time step. This is illustrated in Figure 9.4.

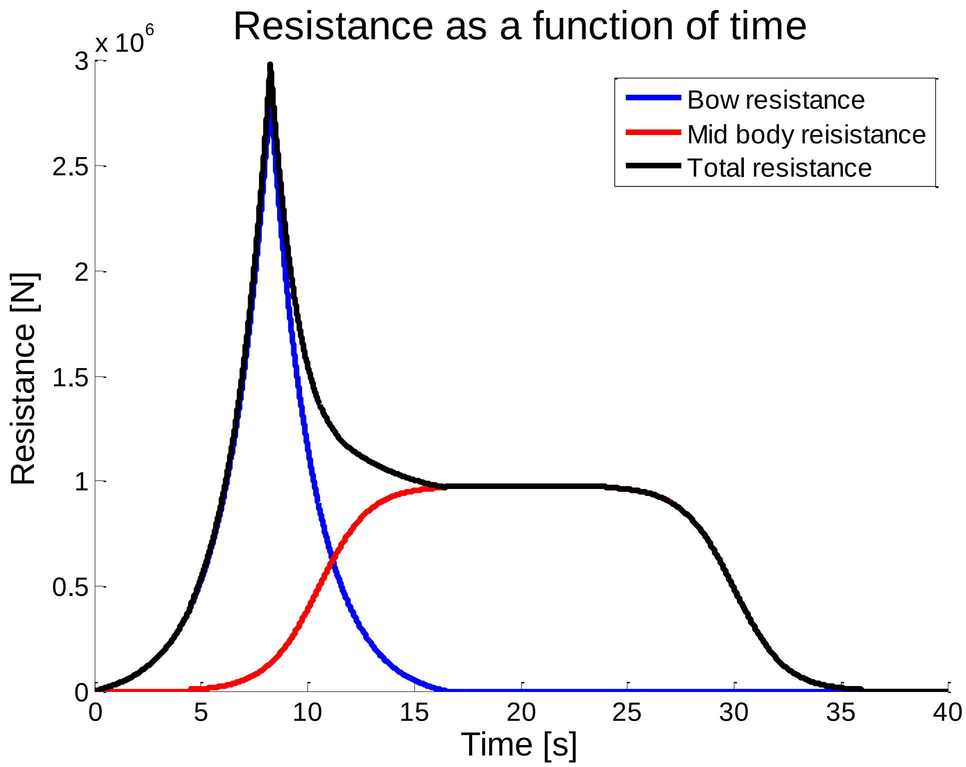


Figure 9.4 Resistance as a function of time

## 9.2 Resistance with various parameters altered

In this section, various parameters are to be changed. This is done to investigate the influence that each parameter has on the resistance. If altering parameters makes the resistance alters as expected, the model is strengthen. The parameters will be altered as shown in the table below.

| Chapter | Parameters altered |
|---|---|
| 9.2.1 | Length of ice ridge |
| 9.2.2 | Length of the vessel |
| 9.2.3 | Breadth of the vessel |
| 9.2.4 | Friction factor |
| 9.2.5 | Internal friction angle |
| 9.2.6 | Effective friction coefficient |

Table 9.1 Altered parameter sequence

All parameters will be explained in the respectively chapter.

### 9.2.1 Resistance with different lengths of the ice ridge

The length of the ice ridge is in this report defined as the length along the motion of direction, see Figure 5.1. The figure also implies that increased length of the ice ridge cause an increased maximum thickness for the ice ridge. Since both the bow resistance and the mid body resistance is a function of the thickness squared, an increased ridge thickness will make a significant impact on the total resistance.

Further, for most cases the length of the ice ridge will not exceed the length of the vessel mid body. An increased length of the ridge will therefore create a larger area where the vessel experience friction against the ice, and thereby higher mid body resistance. Figure 9.5 shows the resistance with different ridge lengths. Due to the fact that bow resistance and mid body resistance both are a function of the thickness squared, both resistances are increasing for increased ridge length. Mid body resistance is in addition also directly affected by the mentioned enlarged area of ice contact, and will experience a larger relative enlargement than the bow resistance.

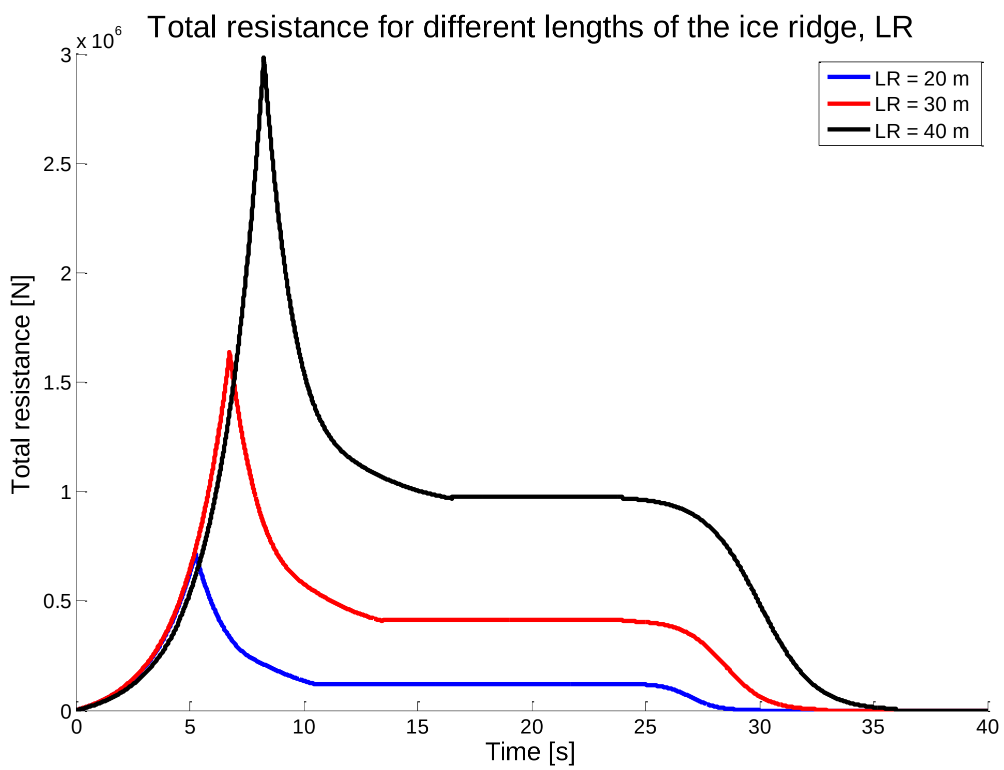


Figure 9.5 Total resistance for different lengths of the ice ridge

### 9.2.2 Resistance with different lengths of the vessel

In the MCSim model, the length between the perpendiculars is by default the numerical value of 80 meter. This value did become one of the reference parameters. Even though the vessels characteristics are already given in the MCSim model, it still gives a valuable insight to investigate how the resistance varies for different vessels lengths. Assuming that the bow length is constant, only the mid body resistance will be influenced by altering the length of the vessel. For an ice ridge shorter than the mid body length, increasing the vessel length will not alter the maximum mid body resistance since the maximum area in contact with ice will be the same. Figure 9.6 illustrates the resistance picture for three different vessel lengths.

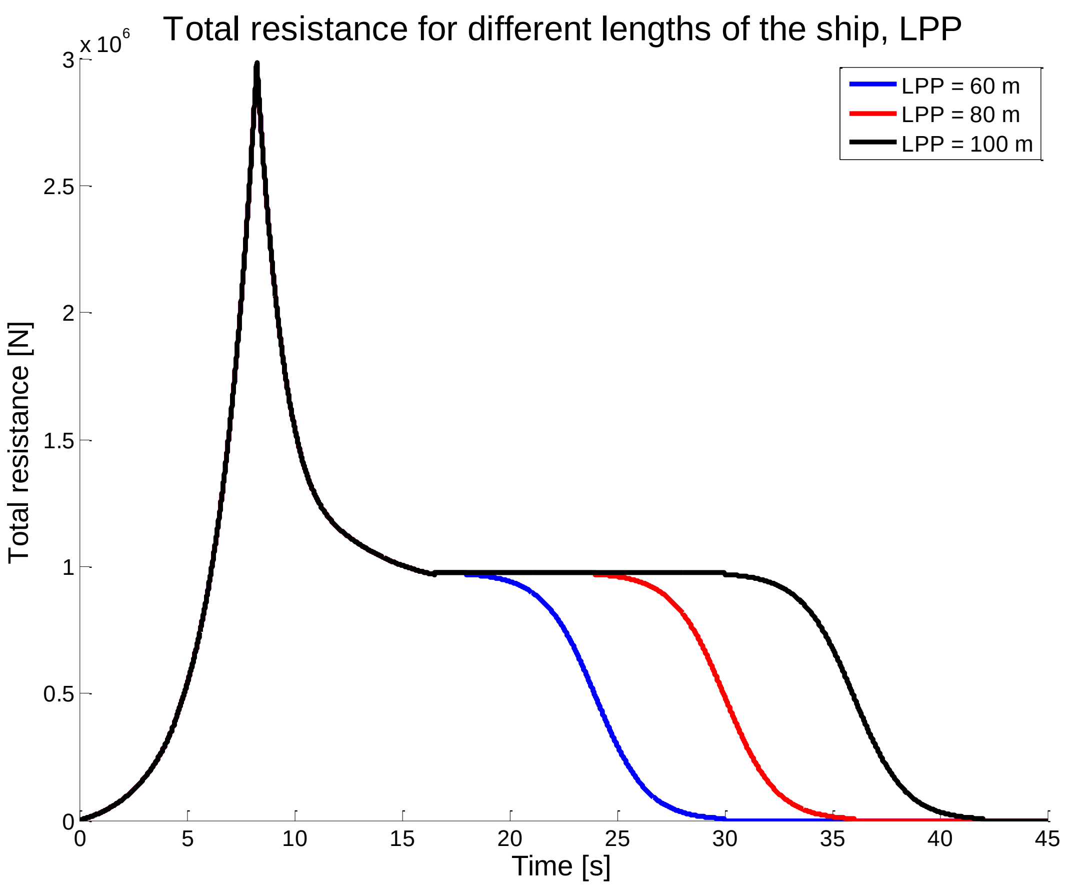


Figure 9.6 Total resistance for different lengths of the vessel

### 9.2.3 Resistance with different breadth of the vessel

In the MCSim model the breadth of the vessel has a numerical value of 17.4 meter. Altering the breadth will give a better understanding of how the resistance is influenced by the different parameters. The mid body has the same ice contact area regardless of the vessels breadth, therefore only the bow resistance will vary with the vessels breadth. Assuming constant speed of the vessel, altering the breadth will not influence the time the bow needs to penetrate the ice ridge. The influence will instead be on the magnitude of the bow resistance. The peak varies linear with the vessels breadth as shown in Figure 9.7.

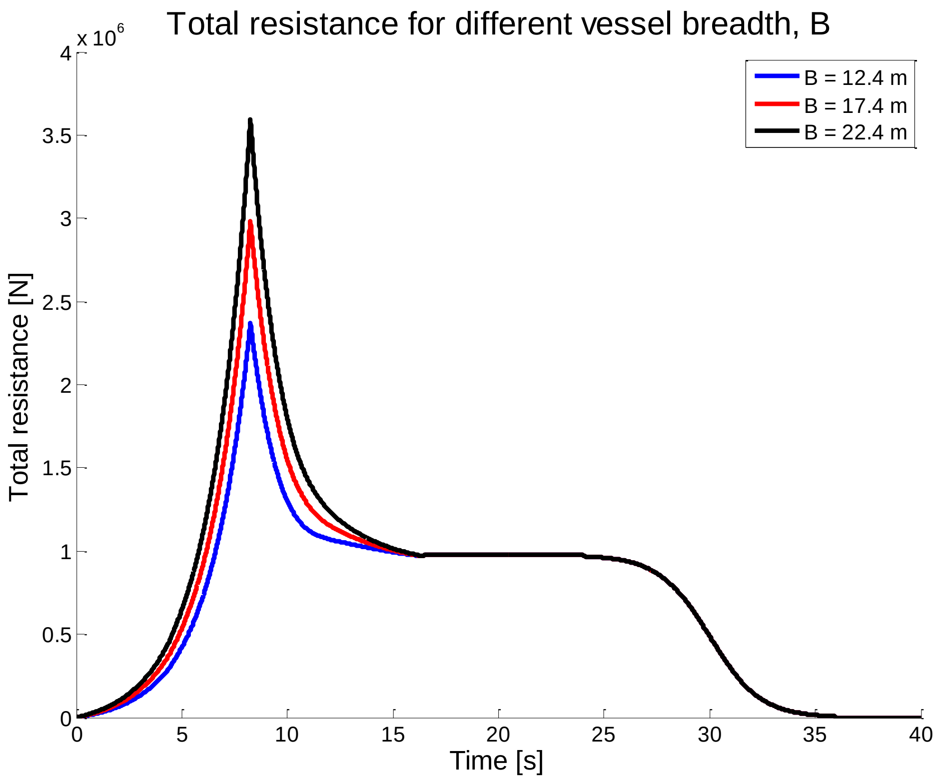


Figure 9.7 Total resistance for different vessel breadth

### 9.2.4 Resistance with different friction factor, N

The friction factor, N, describes how good “grip” the ice can get on the vessel. A factor of zero means no grip, while a factor of 1 means maximum friction. For wet ice on a smooth hull this factor will typically be around 0.2 (Mellor 1980). For dryer ice and rougher vessel surface this factor can increase dramatically. The influence of N on the bow resistance is neglected due to relative short bow length and the fact that the bow already has an angle to the direction of motion, leaving the friction factor less important. The mid body the resistance increase linear with N, as seen in formula(5.25). The total resistance for different values of the friction factor is shown in Figure 9.8

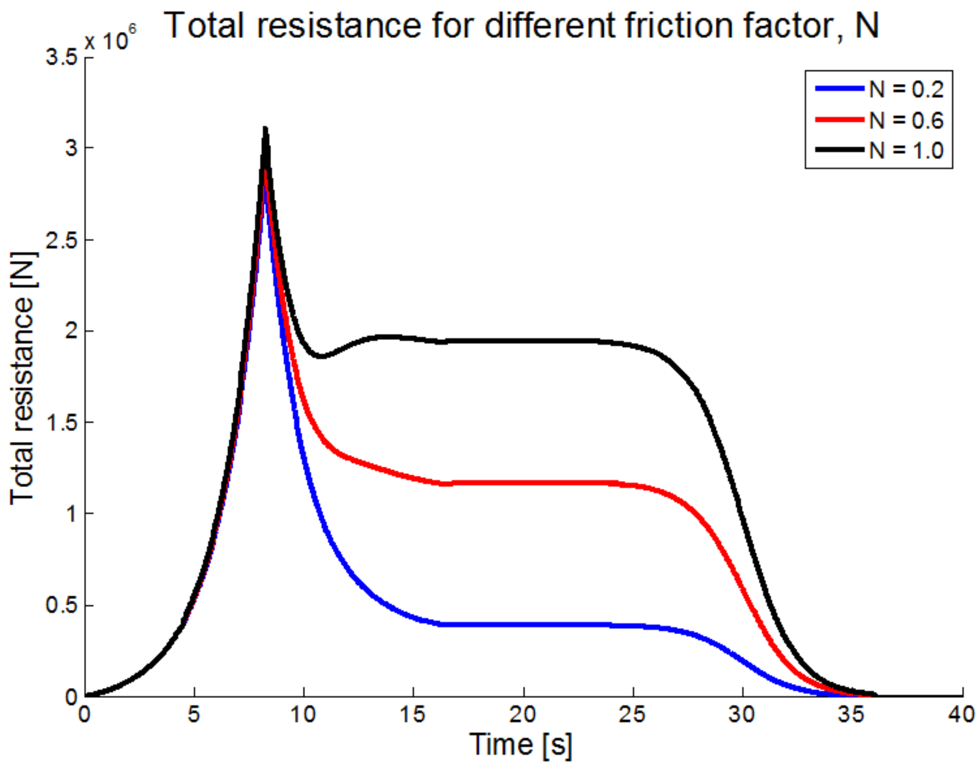


Figure 9.8 Total resistance for different friction factors

### 9.2.5 Resistance with different internal friction angle

The internal friction angle, phi, can be thought as the angle of shear stress. The friction factor can either be calculated from the internal friction angle among other parameters or just be estimated based on experiments. Figure 9.9 show the resistances corresponding to the varying of the internal friction angle. Note that the chance of internal friction angle has an opposite impact on the mid body resistance compared with the bow resistance.

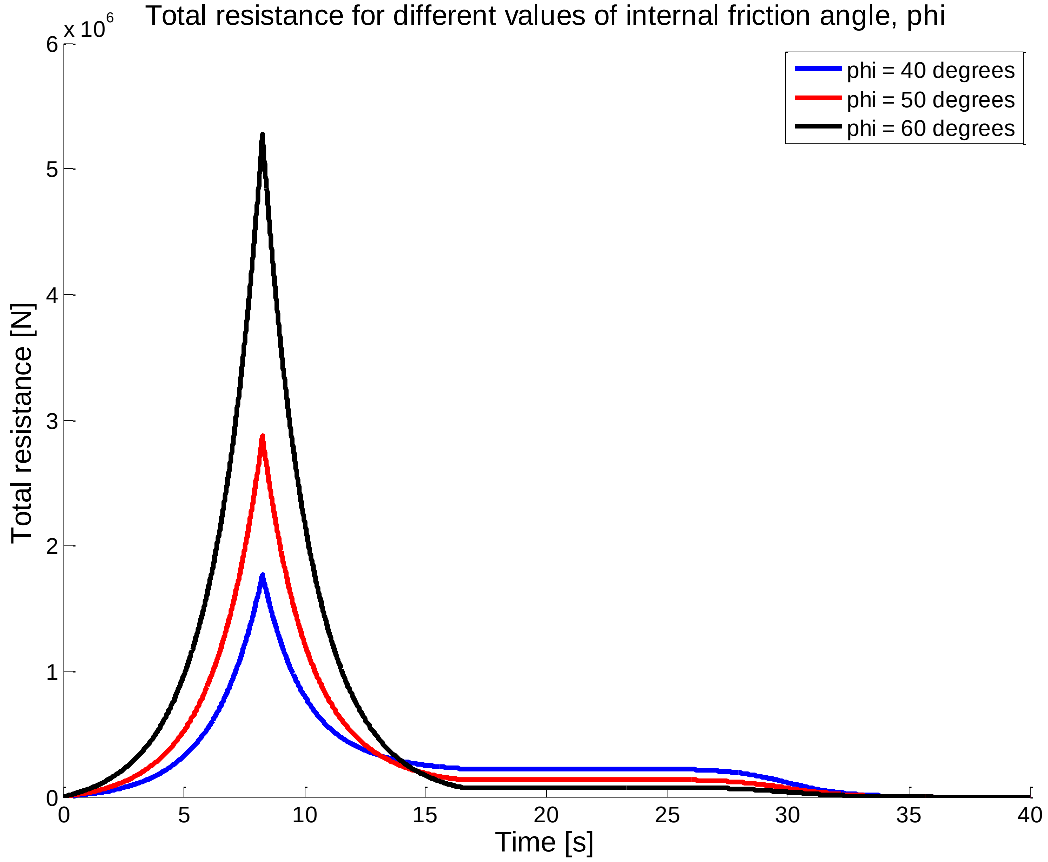


Figure 9.9 Total resistance for different values of internal friction angles

### 9.2.6 Resistance with different effective friction coefficient, my

The effective friction coefficient is not to be mixed up with the friction factor, N. While the friction factor determine how much force that acts on a unit length, the effective friction factor determine how much of this force going in the direction of motion. The mid body resistance will vary linear with the effective friction factor while only the friction part of the bow resistance will vary, this variation will however also be linear. Taking into account that only a part of the bow resistance will vary with the effective friction coefficient, the mid body resistance will be most affected by variation, see Figure 9.10 below.

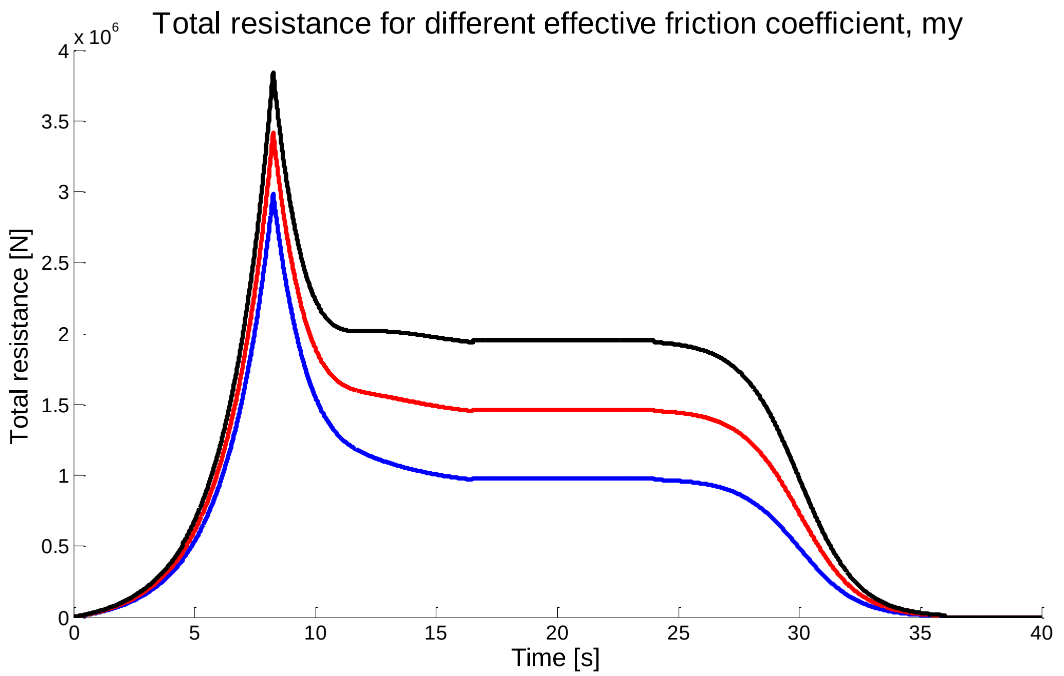


**Figure 9.10 Total resistance for different effective friction coefficients**

## 9.3 Summary

This subsection will give a brief overview of the results presented in this chapter and discuss the main elements of the results. The table below presents a brief overview of the simulation results in this chapter and will be further explained below.

| Overview of the parameter study | | |
|---|---|---|
| **Parameter increased** | **Mid body resistance** | **Bow resistance** |
| Ice ridge length | Increased | Increased |
| Vessel length | Unchanged | Unchanged |
| Vessel breath | Unchanged | Increased |
| Friction factor | Increased | Unchanged |
| Internal friction angle | Decreased | Increased |
| Effective friction coefficient | Increased | Increased |

Table 9.2 Summary of the parameter study

The simulations showed that increased length of the ice ridge would increase the total ice resistance. This is due to the fact that the length of the ice ridge also affects the thickness of the ice ridge. Both the mid body resistance and the bow resistance are a function of the ice thickness squared and were shown to increase significantly with an increase in ice ridge length.

By changing the vessel length the ice contact area will change and cause a higher mid body resistance due to increased friction. This is however only true if the ice ridge has a length larger than the vessel`s length. Such ridges are highly unlikely for a DP-vessel to encounter and would be almost impossible to penetrate. All ridges in this thesis are considered to be shorter than the vessel. The simulation results showed that the vessel length does not affect the magnitude of the ice resistance. Bow resistance remained unchanged while the mid body resistance experienced an increase in duration but remained unchanged in magnitude.

The vessel breath affects the magnitude of the ice resistance. The simulation showed that the mid body resistance remained unchanged for a variation of vessel breaths. This is due to the fact that the ice contact area is constant for different vessel breaths. The bow resistance experienced a big increase when the vessel breath was increased. Results from this chapter indicate that the bow resistance increased linear with increase in the vessel breath.

The results in this chapter showed that the friction factor greatly affected the mid body resistance which is mainly caused by friction. The bow resistance did not get affected by changing the friction.

Two parameters which are less intuitive, the effective friction coefficient and the internal friction angle, were also varied in order to investigate the response of the ice resistance. It was clearly shown that the friction angle greatly affected the bow resistance while the effective friction coefficient affected both mid body and bow resistance.

### 9.3.1 Discussion

The results presented in this chapter indicate that the ice resistance can be difficult to predict, and that it depends on several parameters. The size of the ice ridge is obviously an important factor when predicting the ice loads, but as shown in this chapter, the total ice resistance is not only decided by the ice ridge size. The total ice resistance picture for an ice ridge can vary a lot, depending on the parameters discussed above.

The results of chapter 0 indicate that the ice ridge length, vessel breath and friction factor greatly affects the ice resistance for a vessel penetrating an ice ridge. The vessel length had no real influence on the ice ridge resistance predicted by the ice ridge model used in this thesis.

Changing the different ice resistance parameters in the simulations was an important tool to detect possible weaknesses with the ice ridge model. However, the response to the parameter change was in accordance with the theory and equations in chapter 0. The results are verifying the ice ridge model and are concluded to be realistic and satisfactory.

# 10 Strategies for ice ridge penetration

The main objective of a Dynamic Positioning system is station keeping, i.e. at all time minimizing the vessels drift from any given way point. This can be a difficult task under harsh environmental conditions. Traditionally the challenge for a DP-system has been to provide station keeping for a vessel exposed to wind, current and wave forces.

This chapter suggests features to include in a DP-system in order to make it able to deal with ice ridge collision when in station keeping mode.

## 10.1 The challenge

When investigating anchored vessels or FPSO`s in drilling mode an additional control object appears. These vessels are rigidly connected to the sea bed and it is intuitive that a large vessel drift will cause tension on the riser or anchor line.

For an FPSO in drilling mode it is important that the vessel drift does not cause tension on the risers. Figure 10.1 shows an FPSO connected to the sea bed by risers. It is clear that change of the vessel`s position might cause tension on the risers, and potentially lead to a breach. A vessel drift of a magnitude sufficient to cause tension on the risers is typically caused by harsh weather conditions. In arctic areas drifting ice colliding with a marine vessel could cause large position offset.

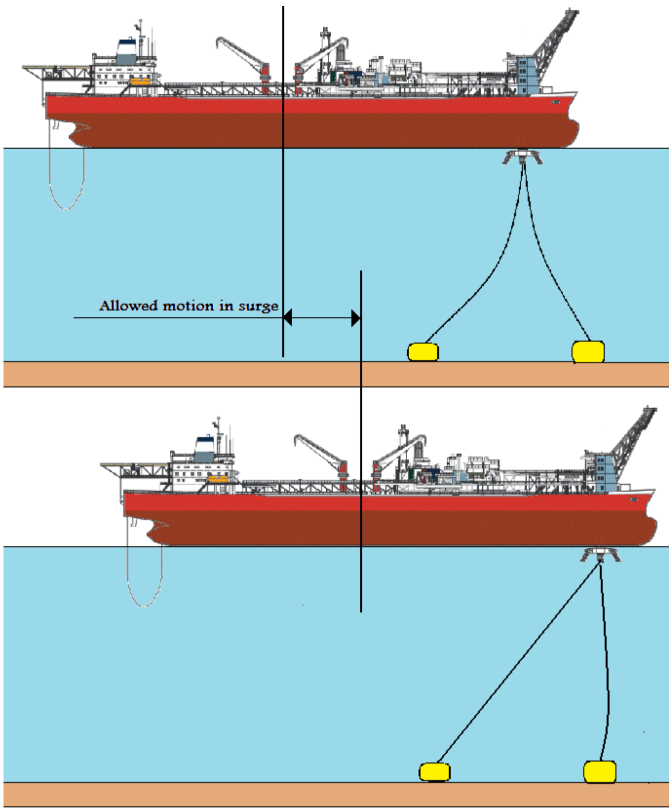


Figure 10.1 Allowed motion in surge for a vessel in DP assisted with mooring lines

An FPSO exposed for conventional disturbances, e.g. storm and rough waves, will typically shut down the production and disconnect the risers to prevent them being exposed of tension. In this master thesis different methods of how to prevent shut down are investigated.

A marine vessels ability to penetrate different ice regimes depends on its size and velocity. The size, or thickness, of an ice obstacle that can be overcome by a vessel is depending of the vessels momentum. For an FPSO in drilling mode it is obvious that the ability to obtain a large momentum is limited by the length of the risers. In this thesis several DP-strategies that take limitations of motion for a vessel into account, will be presented and discussed. By defining an area of allowed vessel motion the DP-system constraints are set. The objective is to create a DP-strategy that achieves good ice crushing properties and maintains a vessel position within the pre-defined area of allowed vessel motion.

The allowed radius of movement i.e. the distance the vessel can drift in any direction without exposing the risers for tension depends on the water depth. Typically a vessel can move a distance of 5-10 percent of the water depth before the risers are exposed for tension. By taking into account the allowed motion, the DP-system will execute a strategy for penetrating an incoming ice obstacle.

## 10.2 Tactics for ice ridge penetration

This chapter will discuss different strategies for penetrating ice ridges. For vessels in DP mode a colliding ice object will pose a threat to the objective of station keeping. The pressure put on the DP-controller depends on the size and porosity of the ice objects. In this thesis three different cases of ice ridge encounters will be assessed.

1. The vessel is hit by a small size ice ridges. In this case the vessels DP-system will have no problem of generating enough thrust and reactive power to withstand the force created by the ice ridge. The ice ridge will be penetrated as it drifts past the vessel that will experience a small offset from the desired position.
2. The vessel is hit by a medium size ice ridge. As the vessel in DP-mode is hit by a medium size ice ridge it will be exposed to forces of such magnitude that the vessel is drifted away from the desired position of station keeping. The vessel will experience a significant position offset but will eventually generate enough thrust to penetrate the ice ridge.
3. The vessel is hit by a large size ice ridge. A vessel that is hit by a large size ice ridge will experience forces of a magnitude larger than the available thrust capacity. In this scenario no reactive DP-system or manual control will allow the vessel to penetrate the ice ridge.

For case 1 the solution is a straight forward DP-controller challenge. A controller with proper controller gains, sufficient to the forces excited by the ice ridge needs to be implemented. Such a re-active DP-controller for incoming small ice ridges is suggested in this master thesis and presented in a previous chapter. In this chapter a pro-active tactic for case 2 and case 3 will be proposed. For case 3 the ice incoming ice ridge is of such a massive character that a proactive DP-system is necessary in order for the vessel to generate sufficient momentum. For case 2 a proactive strategy will be proposed in order to penetrate the ice ridge without exceeding a specific set of limits regarding the position offset.

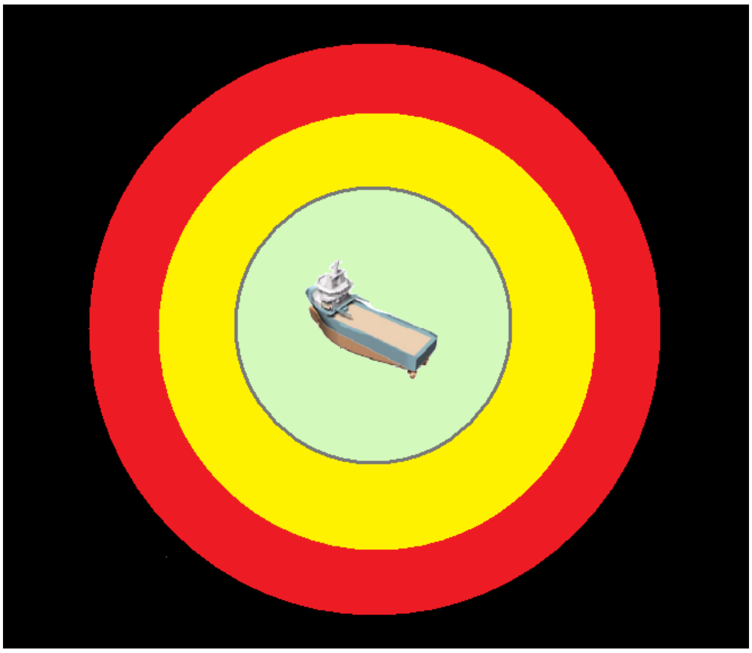

Figure 10.2 Areas of operation

In the Figure 10.2 above there are several areas of operations, each marked with different colors.

**The light green zone** represents the playground, where it is safe to move around. Inside this circle, tactics for encountering incoming ice obstacles can safely be done.

**The yellow zone** represents an area where it is safe to operate, but it will be desirable to return to the green circle as soon as possible. Advanced tactics for encountering ice obstacles will not be perform in this area, and the focus will be an almost full throttle modus to get back to the green area.

**The red zone**, the border between the yellow and the red circle is a disconnect line. All operations are in this area stopped as soon as possible, and an emergency modus is initialized.

**The black zone** is an area where there are safety issues for equipment or/and people. This area is to be avoided for all costs.

In this chapter five different tactics for ice ridge penetration will be presented. There are two main objects of the tactics.

- Avoid large position offset
- Ability to penetrate large ice ridges

### 10.2.1 Tactic 0

A traditional open-water DP-controller as described in chapter 6 will in the simulation and discussions of this thesis is referred to as tactic 0. No special features for ice contact are implemented in this DP-controller. The reference position for tactic 0 will always be at the desired position zero. For a situation where a vessel using DP-tactic 0 and is hit by a ice ridge it is expected that the vessel will be pushed out of position a considerable distance before the proportional and integral action has built up sufficient thrust to penetrate the ice ridge.

The tactics that contains ice breaking features are presented below and are using different methods to maintain good station keeping abilities while colliding with an ice ridge.

### 10.2.2 Tactic 1

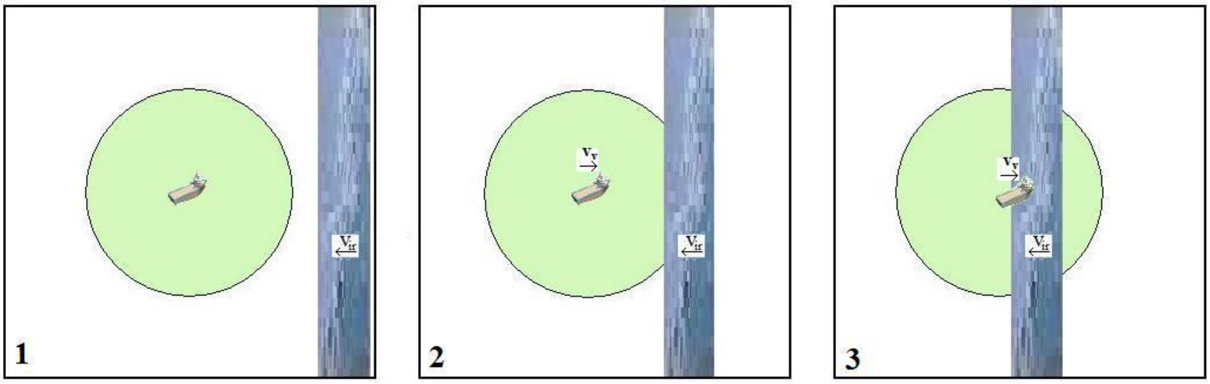


Figure 10.3 Tactic 1

This tactic simply detects an incoming ice ridge as it enters the light green zone and then initiates a vessel motion. This is done by changing the reference point of the DP-controller to the edge of the green zone when the ice ridge reaches the edge as seen in picture number two in Figure 10.3. This causes the vessel to move towards the ice ridge and the goal is to prevent large position offset. After the ice ridge is penetrated the reference signal regains its value of zero.

Pseudo code:

***When*** *ice ridge is past the border*

*- Initiate vessel movement*

***If*** *ridge are fully penetrated*

*- Set position reference to be zero*

***Return***

***End***

***End***

### 10.2.3 Tactic 2

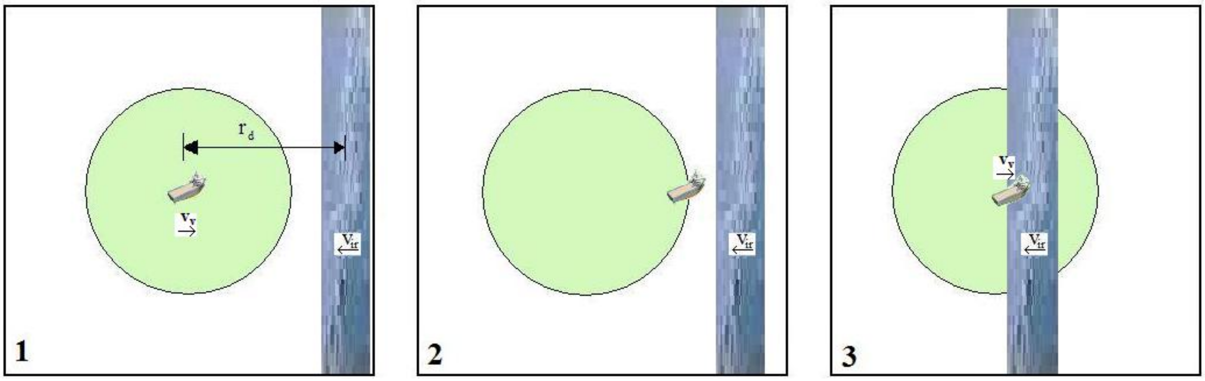


Figure 10.4 Tactic 2

The DP-controller detects an incoming ice ridge and its direction, see picture 1 in Figure 10.4. The detection radius, $r_d$ is for this purpose chosen large. The DP-controller immediately initiates a reference signal sending the vessel to the edge of the green zone with a heading towards the direction of the ice ridge. The vessel will stay on the edge of the green zone while waiting for impact, picture 2. This tactic allows twice the position offset in the direction of the ice ridge`s velocity without being outside the green zone. After the Ice ridge is penetrated the reference signal will regain to zero.

Pseudo code:

**When** *ice ridge is detected*
- *Save that the ice ridge is detected*
- *Set vessel position referense on the border*

***If*** *ridge are fully penetrated*
- *Set position reference to be zero*

***Return***

**End**

### 10.2.4 Tactic 3

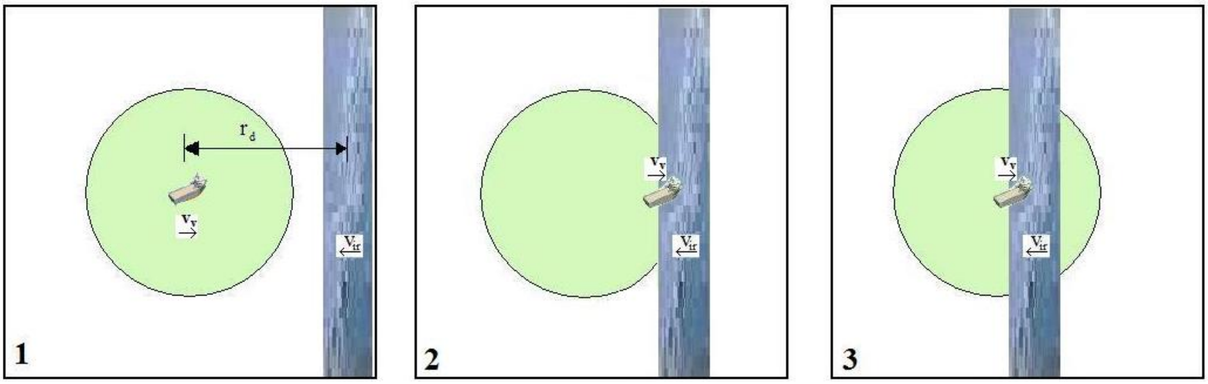


Figure 10.5 Tactic 3

This tactic is intended for ice ridges that are larger than what the DP-controller can withstand with pure thrust power. The objective of this tactic is for the vessel to run full speed at the time of impact. This is done by detecting an incoming ice ridge and its velocity together with knowledge about the vessel response to thrust. The time when the ice ridge will enter the green zone is calculated together with a trajectory path that ensures the vessel to reach full speed within the green zone and reach the edge of the zone at the same time as the ice ridge enters, see picture number two in Figure 10.5. By setting the vessel in movement when the time the vessels need to reach the border distance, $t_{Vneeded}$, equals to the amount of time before the ice ridge hits the border, $t_{Iborder}$, the right moment of action can be found.

Pseudo code:

**When** $t_{Vneeded}$ *is less than* $t_{Iborder}$

- *Initiate vessel movement*

**If** *ridge are fully penetrated*

- *Set position reference to be zero*

**End**

**End**

where $t_{Vneeded}$ is measured and

$$t_{Iborder} = \frac{S_{toborder}}{V_{Iceridge}}, \tag{10.1}$$

where $S_{toborder}$ is the distance from the ice ridge to the border, and $V_{Iceridge}$ is the ice ridge velocity.

### 10.2.5 Tactic 4

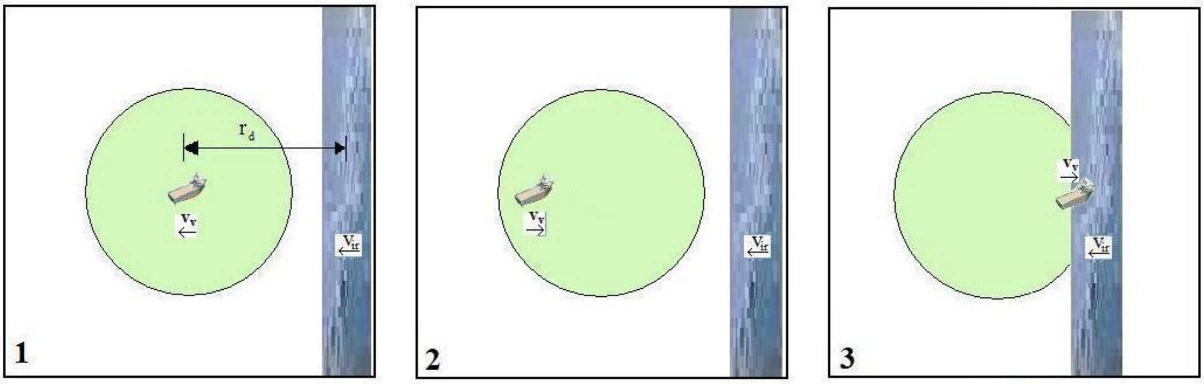


Figure 10.6 Tactic 4

This is the ultimate preparation for a big ice ridge. After the ice ridge is detected the vessel is reversed prior to impact, picture number two in Figure 10.6. This is done to gain even more velocity than in tactic 3. As in tactic 3, both the ice ridge velocity and the vessels response time need to be measured or known values.

Pseudo code:

***When*** *ice ridge is detected*
- *Save that the ice ridge is detected*
- *Reverse the vessel a desired distance, less then the radius of operation*

***While*** $t_{Vneeded}$ *is less then* $t_{Iborder}$
- *Initiate vessel movement*

***If*** *ridge fully penetrated*
- *Set position reference to be zero*

***Return***

***End***

***End***

***End***

### 10.2.6 Tactic 5

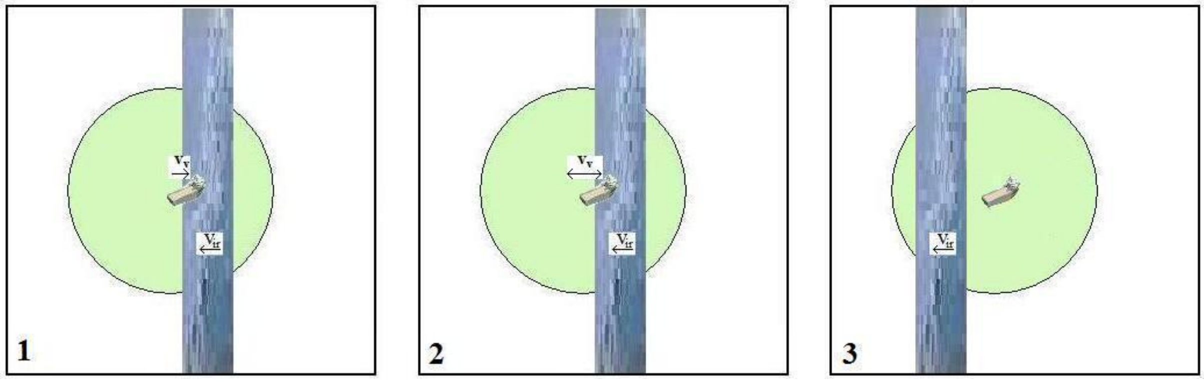


Figure 10.7 Tactic 5

Tactic 5 will be enabled if the vessel gets stuck in the ice. This tactic repeatedly reverses the vessel a desired distance to gain speed and momentum, this is done to be able to ram the ice, see picture number 2 in Figure 10.7. The vessel performs this kind of behavior until the condition is no longer classified as stuck, and the original tactic takes over again. When a stuck condition is detected tactic 5 can be said to overrule the original tactic used.

Pseudo code:

***While*** *stuck*

  *- Reverse the vessel a desired distance*

  ***If*** *reversed*

  *– Initiate movement*

  ***End***

***End***

## 10.3 Switching between tactics

In this thesis the tactic to be used in each specific simulation is predefined. Automatic switching is only used whenever the vessel is stuck, and the “eat and dig approach”, tactic 5, is initiated. The commanded thrust and the relative velocity between the ice and the vessel are monitored. The vessel is considered stuck if the commanded thrust is above 90 % of full thrust capability, simultaneously as the relative ice – vessel velocity is below 0.05 m/s. When a stuck situation is confirmed, the controller performs a reference change by switching to tactic 5. After switching is preformed, the vessel is commanded to reversed, causing the commanded thrust to drop. Without any measure taken, the controller will be switching back and forth rapidly between different tactics, or so-called chattering. This behavior will not give the vessel enough momentum to crush the ice. To avoid this unwanted phenomenon a dwell time switching logic is initiated whenever going from a non-stuck to a stuck situation. This logic ensures that the vessel will have time to back up a desired distance before trying to ram the ice. This dwell time behavior however, is not desired when a stuck situation is detected. For this case, time may be precious, and it is desirable to immediately reverse the vessel. For an illustration of the switching logic see the flowchart in Figure 10.8.

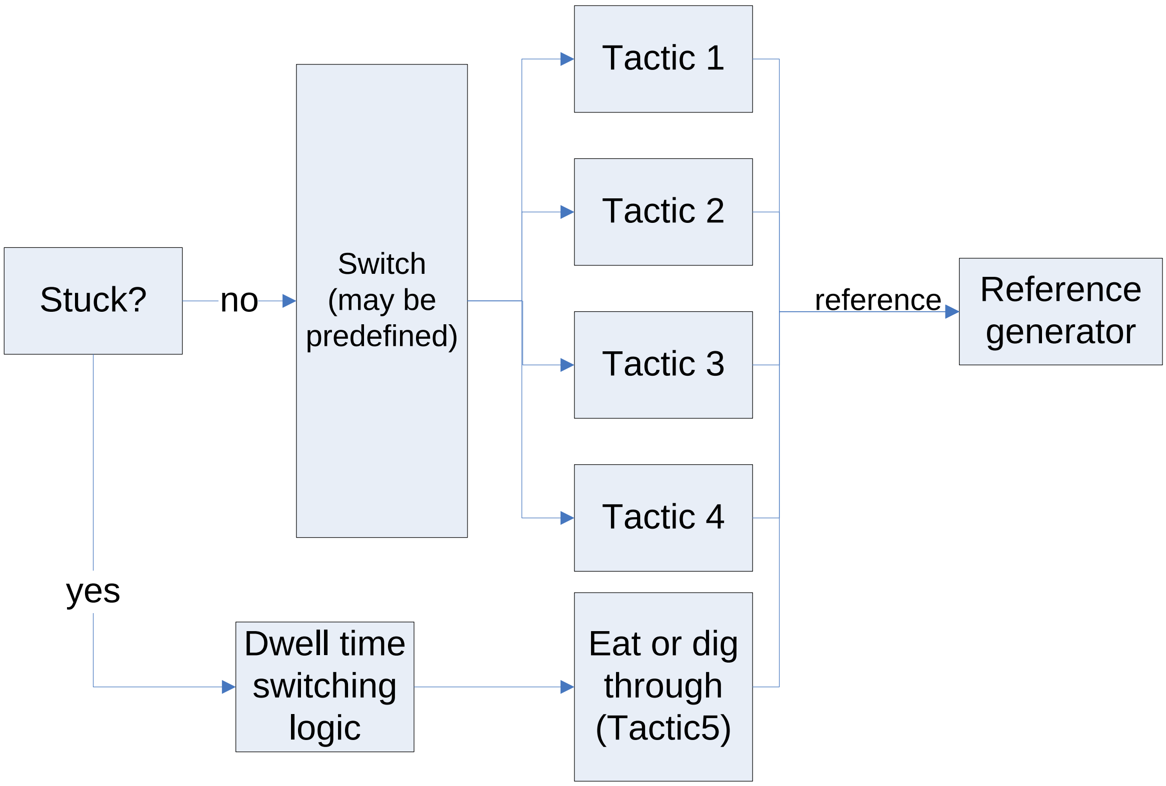


Figure 10.8 Flowchart showing the different tactics

## 10.4 Sensors

Detailed knowledge about the incoming ice ridge is vital in order to execute the different tactics described in the sub-section above. The size, shape and ice velocity must be detected which require a high technological sensor system. This thesis is a conceptual study where different tactics of ice ridge penetration are proposed and discussed. Full state feedback is used and all ice properties are assumed known. The challenge of making a complete sensor system is not dealt with in this thesis.

## 10.5 Possible errors and assumptions for the DP-tactics

Several possible errors have to be considered when using the tactics described in this chapter. The errors include sensor and measurement errors or wrong assumptions about the ice ridge size or properties. Such errors can for instant cause an overshoot in position, which for worst case scenario could cause damage on equipment or even human injury. Ice properties will even with good sensor-ability be a highly uncertain area, due to the huge role of the ice porosity. Therefore, as for any good DP-system, an emergency routine should automatically be initiated if a huge offset in desired position and velocity relative to actual position and velocity are detected. This routine should stop any ongoing operation, and fully concentrate on avoiding any dangerous situation.

# 11 Simulations and results while using different DP-tactics

## 11.1 Introduction

Several simulations are presented in this chapter. Simulations are performed in order to test the performances of the DP-system in open water and to test the different DP-tactics. Three of the tactics are tested against two different ice conditions in order to detect possible weaknesses with the tactic.

First the result of a DP-system for a marine vessel operating in open water with a change of reference position is presented to show a satisfactory behavior. The open water DP-system is then exposed to forces representing an incoming ice ridge in level ice to create a basis of comparison. Subsequently the performance of the open water DP-system is evaluated against the performance of the special purpose DP-systems using the different ice breaking tactics as described in chapter 0. Table 11.1 below gives an overview of the simulation basis for each of the controller tactics.

| Simulation environment for the different tactics | | | | | |
|---|---|---|---|---|---|
| **DP-controller** | **Level ice** | **Ice ridge** | **Current** | **Waves** | **Wind** |
| Tactic 0 | Yes | Yes | Yes | No | Yes |
| Tactic 1 | Yes | Yes | No | No | No |
| Tactic 2 | Yes | Yes | No | No | No |
| Tactic 3 | Yes | Yes | No | No | No |
| Tactic 4 | Yes | Yes | No | No | No |
| Tactic 5 | Yes | Yes | No | No | No |

Table 11.1 Simulation environment

None of the simulations are done with wave disturbance present. This thesis is a conceptual assessment of various methods to automatically maintain station keeping for a vessel colliding with different ice regimes. Full state feedback is used and no filtering or state estimation are done. The wave forces are therefore excluded from the simulations. An observer should be included in order to test the performance for the DP-system when it is exposed to wave forces. In this thesis it is assumed that an ice ridge frozen into level ice represents the largest threat to a vessel in station keep mode and is therefore the main ice regime used in this thesis to test the performance of the various tactics.

## 11.2 The simulation study

The simulations are performed using the MCSim, described in chapter 8, as a platform. A control system featuring an LQ controller, reference model and thruster dynamics are used in the simulated DP operation. The level ice and ice ridge models presented in chapter 0 will be used in the simulations as a representation of the external forces. Except for the demonstration of the DP-system in open water all simulations presented in this chapter are done with ice load as the only external force. For all cases the ice ridge is initially positioned a predefined distance from the vessel and is drifting towards the vessel with a constant velocity. All simulations, except for tactic 5, are done with the objective to achieve station keeping inside the "green zone" which is discussed in chapter 0.

| Overview of the different tactics | |
|---|---|
| **Tactic** | **Description** |
| Tactic 0 | The traditional DP-system that has not been modified in order to deal with incoming ice resistance. |
| Tactic 1 | Initiates a forward motion towards the incoming ice ridge as the ridge enters within a pre-defined area. |
| Tactic 2 | Station keeping ahead of the desired position when an incoming ice ridge is detected to allow a larger pushback distance without exceeding the "green zone". |
| Tactic 3 | Detects ridge velocity and distance from the vessel in order to hit the ridge with a forward momentum and still stay within the green zone. |
| Tactic 4 | Based on the same logic as tactic 3 but is reversing on detection of the ice ridge to gain a larger forward momentum. |
| Tactic 5 | Not related to the different zones but is engaged when a vessel is stuck in an ice ridge. Will then reverse to ram the ridge repeatedly until full penetration. |

Table 11.2 Tactic overview

Unless otherwise is specified the simulations in this chapter are done with vessel properties provided by the MCSim and the ice properties specified in Table 11.3. The ice resistance calculations are based on the ice properties as described in the table below.

| Vessel properties from MCSim | | |
|---|---|---|
| LPP | 80.0 | [m] |
| Breadth | 17.4 | [m] |
| Draught | 5.6 | [m] |
| Displacement | 6000 | [m^3] |
| **Ice properties** | | |
| Level ice thickness | 0.5 | [m] |
| Ice ridge length | 20 | [m] |
| Ice drift velocity | 0.8 | [m/s] |

Table 11.3 Vessel and ice properties

An outline of the chapter is presented in Table 11.4 below. A total of ten simulations are carried out. Tactic 1, Tactic 3 and Tactic 4 are simulated for two different ice conditions in order to detect weaknesses of the tactics regarding overshoot. The traditional DP-system is initially tested in open water in order to conclude with an acceptable performance. Next the traditional DP-system is exposed to incoming ice obstacles in order to create a basis for comparison for the other tactics. For Tactic 2, overshoot is not an issue and the simulation is done only for the case of an incoming ice ridge in level ice.

| Simulation Outline | | |
|---|---|---|
| **Simulation** | **Controller** | **Test scenario** |
| 1 | Tactic 0 | A traditional DP-system tested with current and wind forces |
| 2 | Tactic 0 | A traditional DP-system exposed to level ice and ice ridge |
| 3 | Tactic 1 | Tactic 1 is applied for an incoming ice ridge in level ice |
| 4 | Tactic 1 | Tests Tactic 1 when the ice ridge is smaller than expected |
| 5 | Tactic 2 | Tactic 2 is applied for an incoming ice ridge in level ice |
| 6 | Tactic 3 | Tactic 3 is applied for an incoming ice ridge in level ice |
| 7 | Tactic 3 | Tactic 3 is tested for an unexpected small ice ridge in level ice |
| 8 | Tactic 4 | Tactic 4 is applied for an incoming ice ridge in level ice |
| 9 | Tactic 4 | Tactic 4 is tested for an unexpected small ice ridge frozen in level ice |
| 10 | Tactic 5 | DP-system automatically switches to tactic 5 when stuck in the ice |

Table 11.4 Overview of the ten simulations carried out

### 11.2.1 The traditional DP-system in open water

In order to use the Tactics described in chapter 0 a traditional DP-system was made to be used as a platform for the different tactics. This chapter will prove the performance of the traditional open water DP-system.

The motivation behind this simulation is to show acceptable performance for the open water DP-system. In this simulation the vessel is exposed to current and wind forces.  Zero is set as the initial reference position. After 20 seconds the reference position in surge is changed to 10 meters while the reference position for sway and yaw is kept at zero. Figure 11.1 shows the position and reference position in surge, sway and yaw. The surge position follows the reference in an acceptable manner. The wind and current forces initially create an offset between the Yaw and Sway position and reference but the performance is sufficient to conclude with an open water DP-system that achieve its objectives.

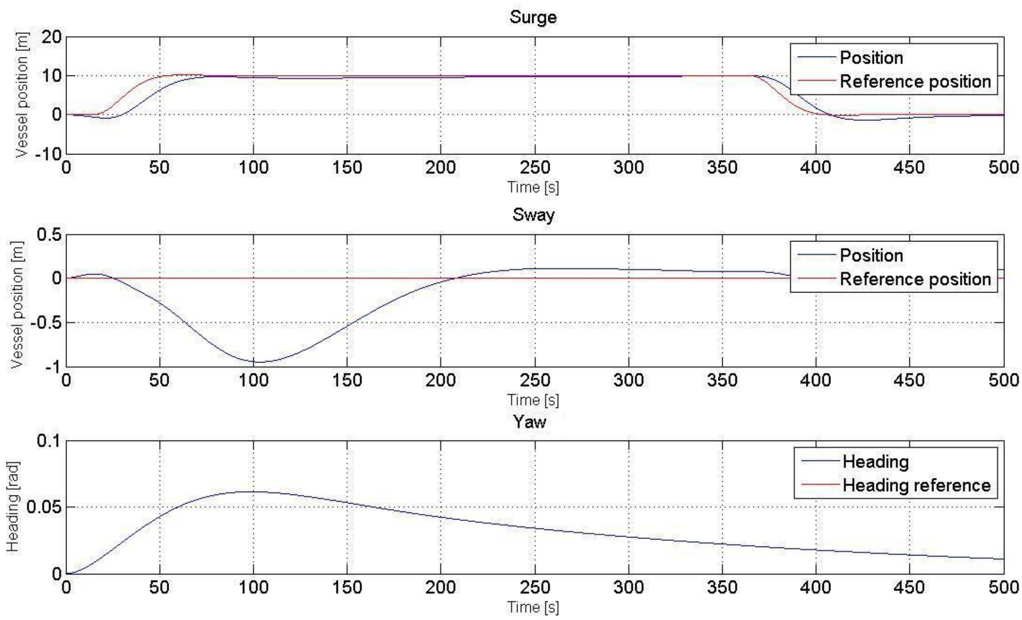


Figure 11.1 Simulation1:  Position surge, position yaw and heading for a simulation in open water

Figure 11.2 below shows the controller effects in surge, sway and yaw. In surge the derivative and proportional effect experience an explosive increase as the reference position in surge is changed to 10 meters. The integral effect in surge increases to a level where it stabilizes to compensate for current and wind forces. The controller effect in yaw and sway has to compensate for the wind and current forces. And will work together in order to stabilize the motion around the reference position.

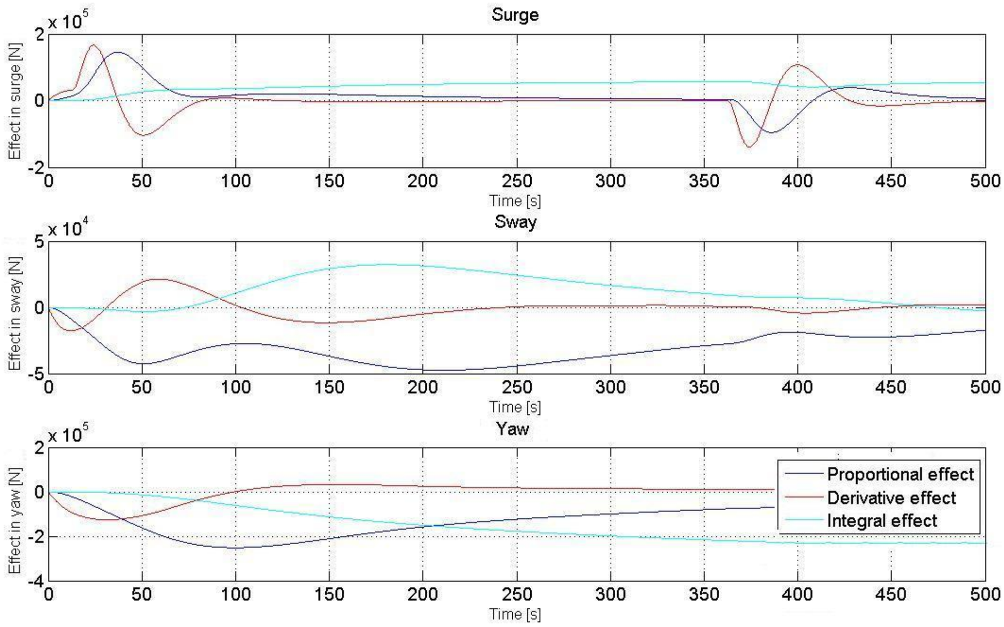


**Figure 11.2 Simulation 1: Controller effect for the traditional DP-system in open water**

### 11.2.2 Tactic 0

Figure 11.3 illustrates the performance for the open water DP-system the vessel in station keeping mode is hit by a drifting ice ridge. The vessel position in surge, velocity in surge, ice resistance in surge and controller action in surge as the ice ridge is penetrated is shown in the figure. Initially the vessel is pushed behind about 20 meters before advancing towards the reference position at zero.

This result implies that if the vessel was in drilling mode and having an acceptable radius of motion of less than 20 meters, the outcome of an ice ridge collision can be catastrophic.

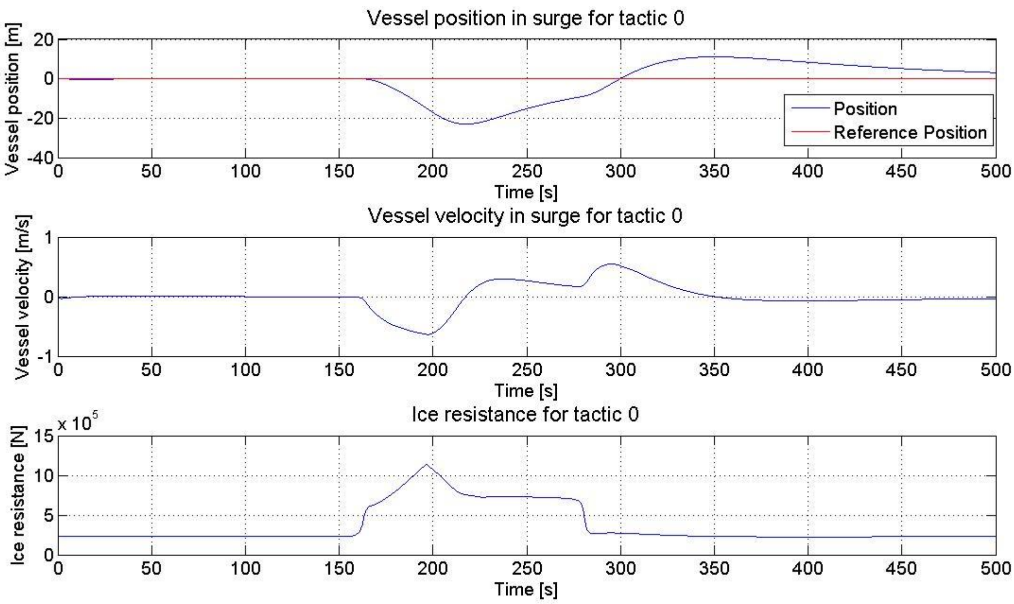


Figure 11.3 Simulation 2: Traditional DP-system exposed to level ice and ice ridge

The DP-system performance can be explained by the sudden impact with the massive ice ridge which forces the system out of position and initiates a thrust in the desired direction. The vessel experiences a large position offset before it has generated enough thrust to penetrate the ice ridge. This property is due to the time delay in the integral action and the fact that the proportional action is dependent on the distance from the desired position rather than the actual ice resistance it has to overcome. The generated thrust is shown in Figure 11.4 below.

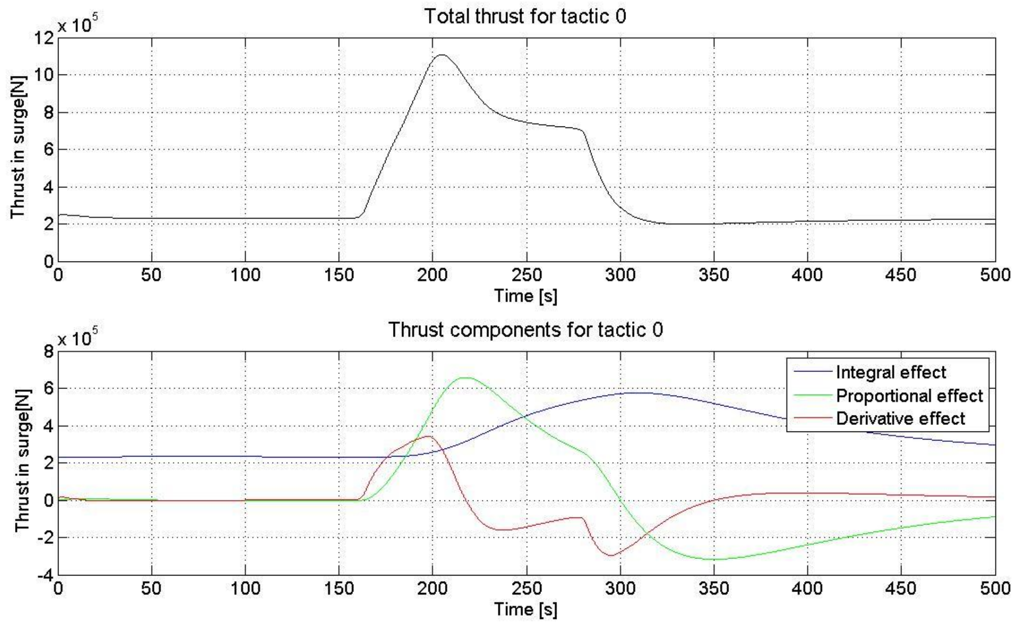


**Figure 11.4 Simulation 2: Total thrust and thrust components in ice ridge and level ice**

### 11.2.3 Tactic 1

As an attempt to reduce the position experienced in the previous simulation, the DP-system was implemented with the features of "Tactic 1" as described in chapter 0

Figure 11.5 and Figure 11.6 presents the results of a simulation where a vessel is colliding with an ice ridge frozen into level ice while in station keeping mode. The vessel uses a DP-system implemented with Tactic 1 which means that the ice ridge is detected when it enters a pre-defined area where and a DP-reaction is initiated. By changing the reference position the DP-system will generate forward thrust which helps the vessel overcome the ice resistance.

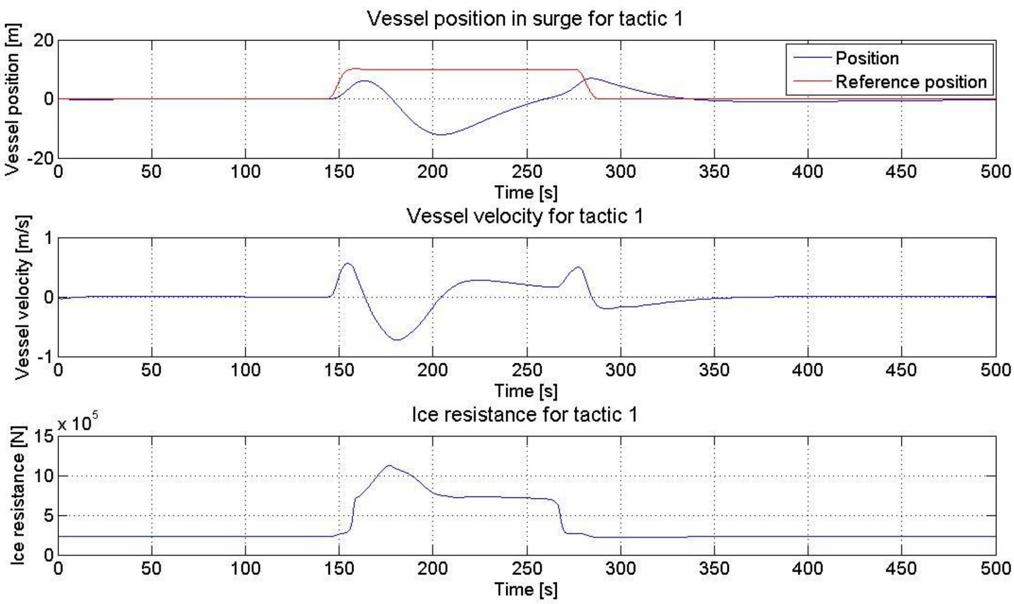


**Figure 11.5 Simulation 3: DP-controller using tactic 1 exposed to level ice and ice ridge**

As illustrated in Figure 11.5 the vessels position is less than 10 meters ahead of the desired position when it is hit by the ice ridge. The vessel is pushed back a several meters by the ice ridge before it continues towards the new reference position of 10 meters. After the ridge is penetrated the reference position is restored to zero.

As shown in Figure 11.6 the total thrust experience two significant jumps. These jumps are caused by the derivative effect. The change in the reference position causes a drastic reaction from the derivative contribution.

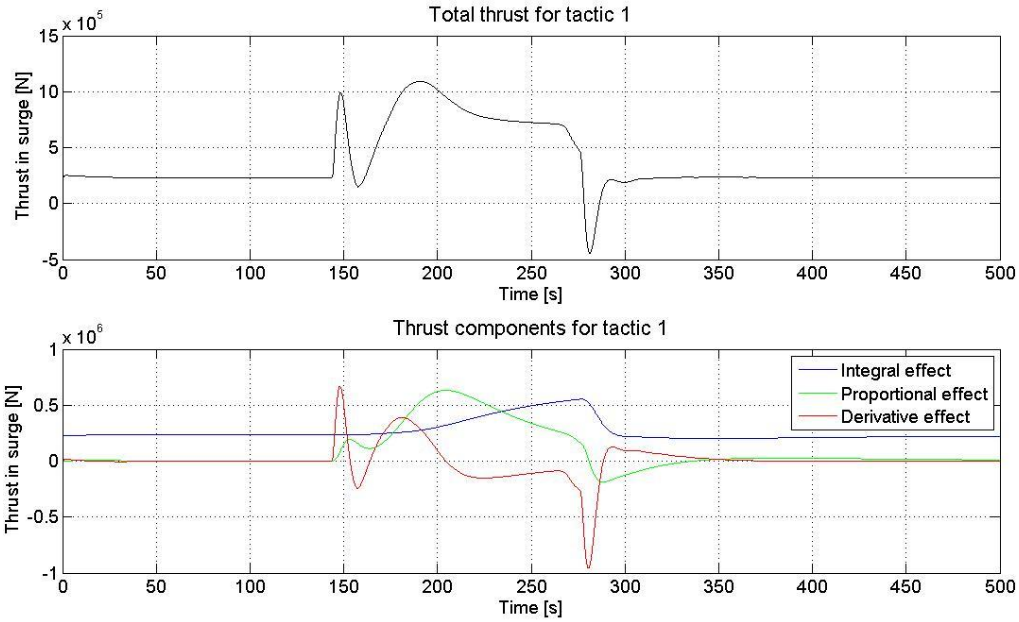


Figure 11.6 Simulation 3: A DP-system using tactic 1 exposed to level ice and ice ridge

The integral effect will build up during the period the vessel has been pushed out of position by the ice ridge. To avoid a big overshoot the integral effect is restored to the initial value, which equals level ice resistance, when the ice ridge is fully penetrated. This event causes the jump in the integral action.  Two times during the simulation the reference position is changed. One reference change is made after the incoming ice ridge is detected and countermeasures are initiated. The second reference is made when the ice ridge is fully penetrated and the vessel is desired to return to its position at zero. These reference changes are reflected by the jump in the derivative and proportional action.

A DP-system using tactic 1 has throughout the simulations presented in this chapter proved to perform far better than the traditional DP-system when colliding with ice ridges. However, if the incoming ice ridge is less massive or smaller than expected, the risk of position offset due to overshoot is present. Figure 11.7 illustrates the case where Tactic 1 is applied and the ice ridge excites only 1/100 of the resistance as in the previous simulation.

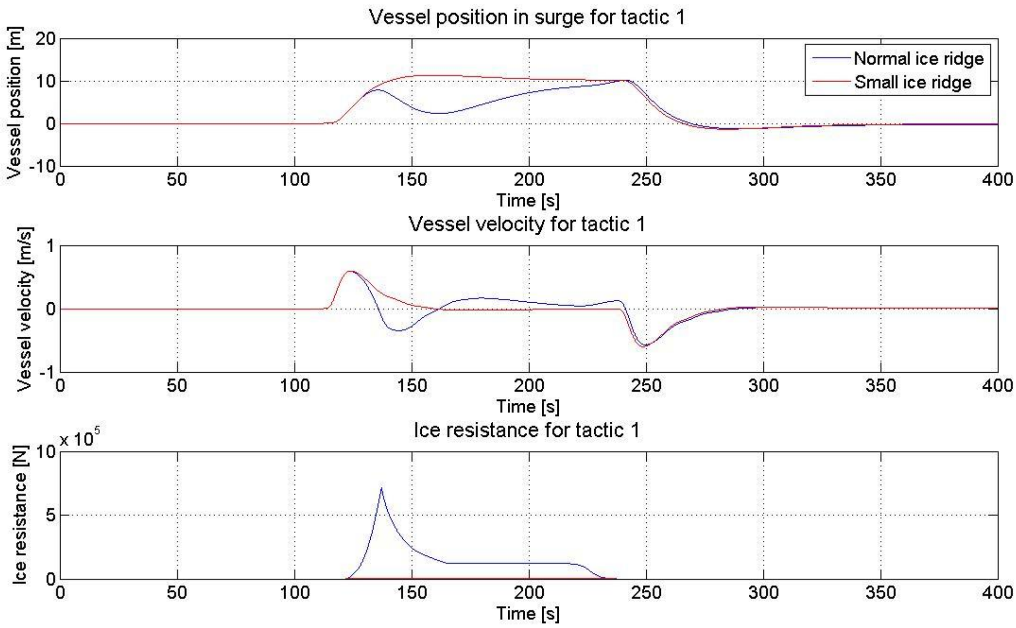


Figure 11.7 Simulation 4: Comparison of an encounter with small and normal sized ice ridge

As illustrated in Figure 11.7 the surge position is still within acceptable limits. This suggests that there is no significant risk of getting overshoot when encountering an unexpected small ice ridge. As long as the reference position always is set to be within the area of acceptable motion the vessel will align to that position.

### 11.2.4 Tactic 2

Tactic 2 is a simple tactic with regards to ensure station keeping within a desired area. When an ice ridge is detected the DP-system automatically set the new reference position to the edge of the area of allowed motion. The vessel bow should be headed towards the incoming ridge. The vessel will then move to the new reference position and stay there on station keeping mode. When stationed at the new reference position the DP-system operates like a traditional DP-system when hit by the incoming ice ridge. Tactic 2 may allow the vessel to be pushed back a distance two times the allowed motion radius, which allows the DP-system more time to generate enough thrust to penetrate the ice ridge without leaving the desired area.

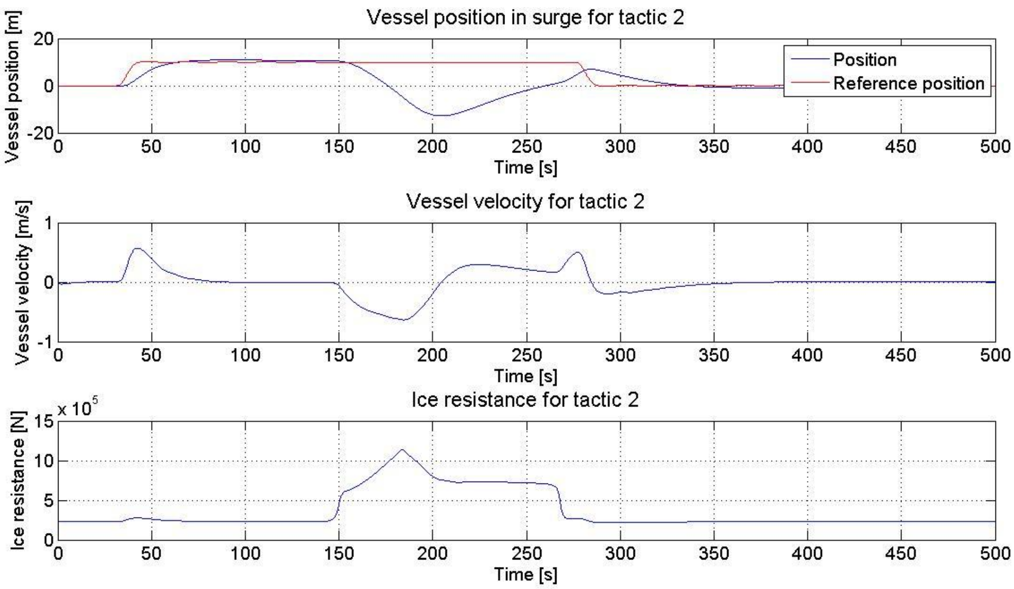


**Figure 11.8 Simulation 5: DP-system using tactic 2 exposed to level ice and ice ridge**

As the vessel is already in station keeping mode when hit by the ice ridge the risk of overshoot is considered to be small.

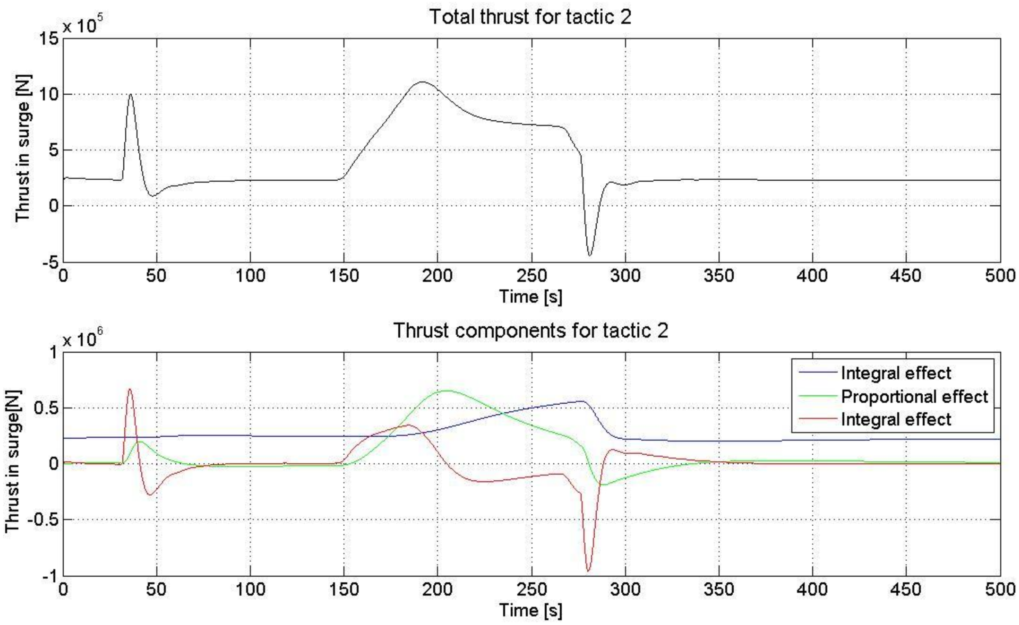


**Figure 11.9 Simulation 5: DP-system using tactic 2 exposed to level ice and ice ridge**

Two changes of the reference set point will cause two jumps in the thrust. When the ice ridge is fully penetrated the set point will be reset to zero and the integral effect restored to the level ice value which causes the jump in the integral effect.

### 11.2.5 Tactic 3

The foundation of tactic 3 is to generate a forward vessel momentum before the ice ridge collision in order to improve the ice breaking abilities. The tactic is relying on the ice ridge resistance to absorb the vessels momentum so that the vessel will not just run through the ice ridge and violate the motion limitations.

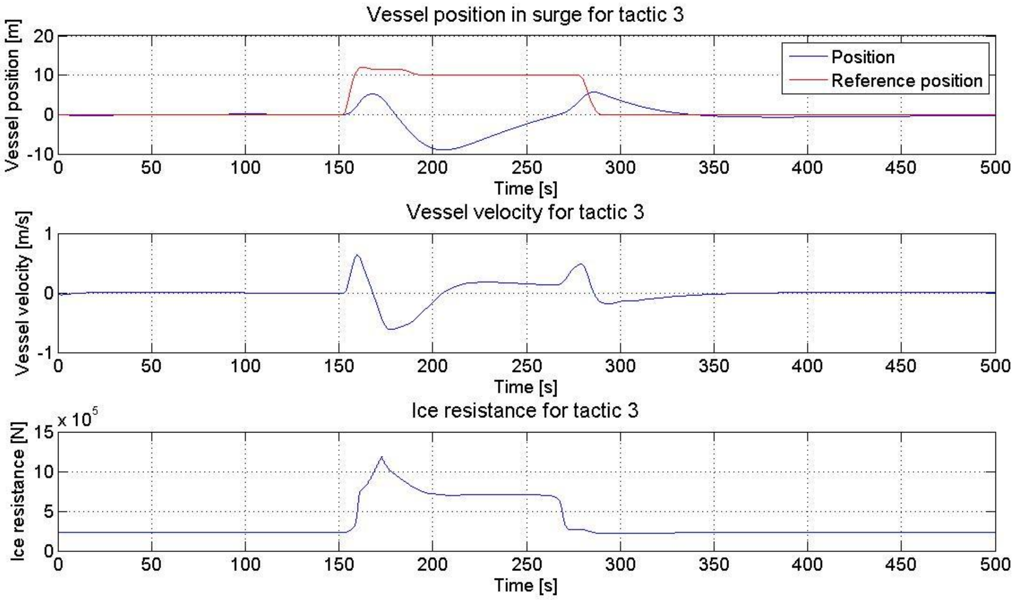


Figure 11.10 Simulation 6: A DP-system using tactic 3 while exposed to level ice and ice ridge

Tactic 3 is more complicated than tactic 1 and tactic 2 but has larger ice-crushing potential. As illustrated in Figure 11.10 the vessel operates with a significant velocity when colliding with the ice ridge. The momentum prevents the vessel from being pushed backwards after it is hit by the ice ridge. Vessel position in surge as illustrated in the figure above indicates that tactic 3 maintains station keeping within 10 meters from the desired reference position.

Figure 11.11 shows the thrust development of the simulation. The integral effect is reset to level ice values after the ice ridge is penetrated which causes the jumps in the integral effect. The initial jumps in the derivative and proportional effect is caused by the reference change made pre-collision in order to build up a forward momentum. The final jump in proportional and derivative effect is caused by the reference change made after ridge penetration in order to restore the vessels position to zero.

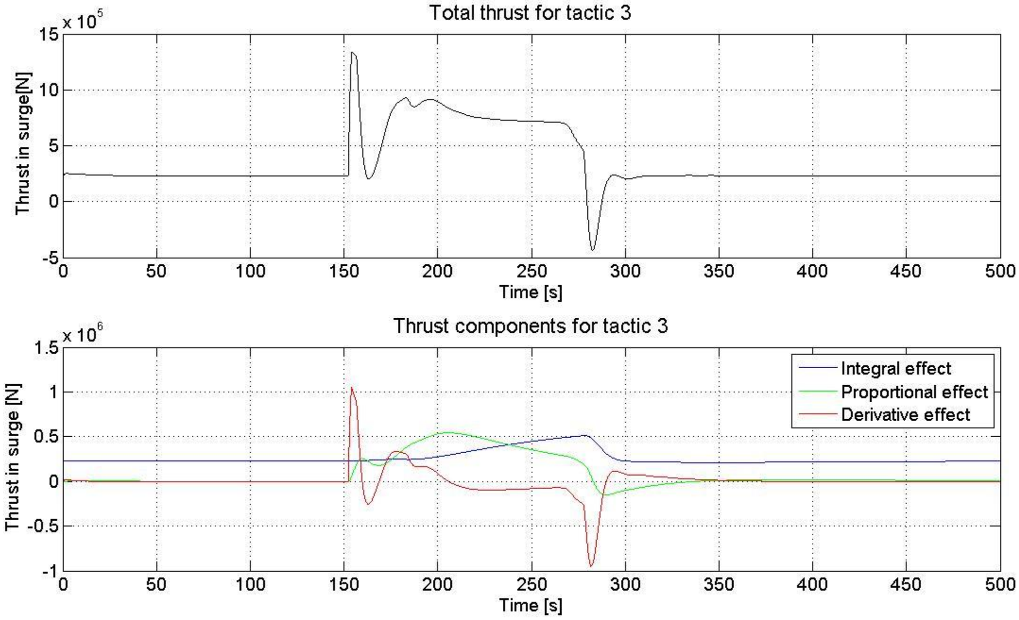


**Figure 11.11 Simulation 6: A DP-system using tactic 3 while exposed to level ice and ice ridge**

Tactic 3 generates a momentum and relies on the ice ridge resistance to stop its motion, this property introduce a risk of overshooting. If the colliding ice ridge appears to be smaller than expected, the vessel will not meet much resistance and might experience difficulties stopping the surge motion before leaving the "green zone". This case is illustrated in Figure 11.12 which plot both encounter with a normal ice ridge and with a small ice ridge.

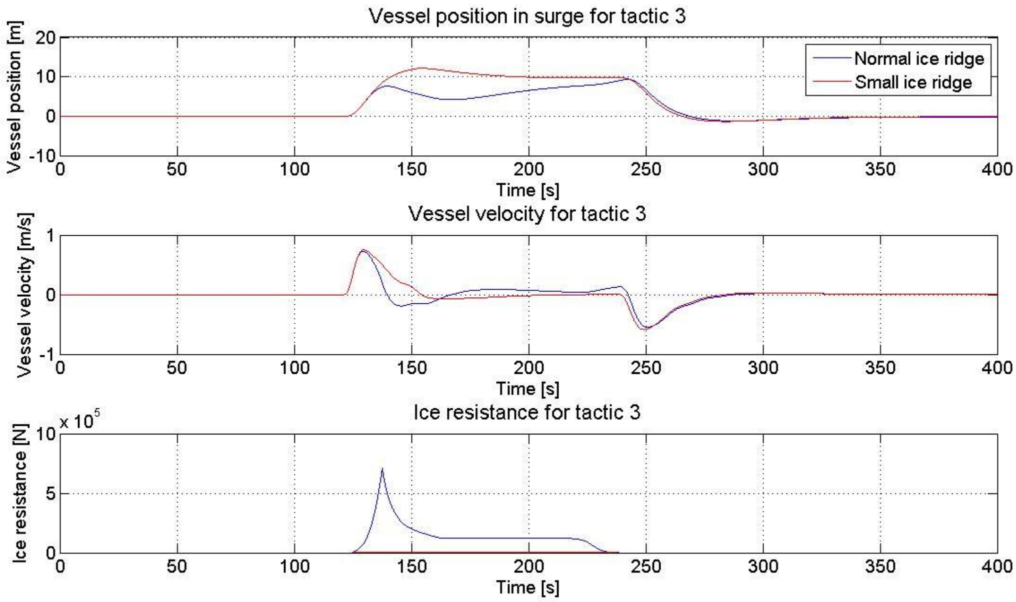


**Figure 11.12 Simulation 7: Tactic 3 in unexpected small ice ridge**

The simulation corresponding to Figure 11.12 is done without any level ice present. The target of the tactic is to hit the ice ridge at distance ahead of the desired reference position and to use the forward momentum to penetrate the ice ridge. Figure 11.12 illustrates with the blue line the case where the ice ridge is massive enough to absorb the vessel momentum and, with a red line, a case where the ice resistance has almost no effect on the vessel velocity. The figure above clearly shows how a normal sized ice ridge will affect the vessel velocity and how a small ice ridge will almost not affect it at all. The resistance caused by the normal sized ice ridge is sufficient to keep the vessel stationed within 10 meters ahead of the reference position while the in case of a small ridge the vessel will continue forward to exceed 10 meters. It is indicated by the figure above that the overshoot when encountering the small ice ridge is not very large. If this tactic was to be used in a borderline operation, with 10 meters limit of motion, even a small overshoot could pose a threat to the drilling operation.

### 11.2.6 Tactic 4

Tactic 4 is based on the same principles as tactic 3, generating a forward momentum in order to break the ice. The difference between tactic 3 and 4 is that tactic 4 react on an incoming ice ridge by first initiating a reversed motion. When the ridge is getting close to the "green area" the vessel is moving forwards and towards the ice ridge. The principle behind tactic 4 is to reverse the vessel to gain a larger distance to accelerate, i.e. creating a larger momentum, before impact with the ice ridge.

Figure 11.13 and Figure 11.14 shows the result of a simulation done for a vessel using tactic 4 and colliding with an ice ridge frozen into level ice. The results show very good station keeping properties, where surge position is kept within 6-7 meters. The results obtained by using tactic 4 are slightly better than the ones achieved by using tactic 3 with respect to surge position. However, due to the larger velocity of tactic 4 it is reasonable to assume that this tactic has the highest ice breaking capability.

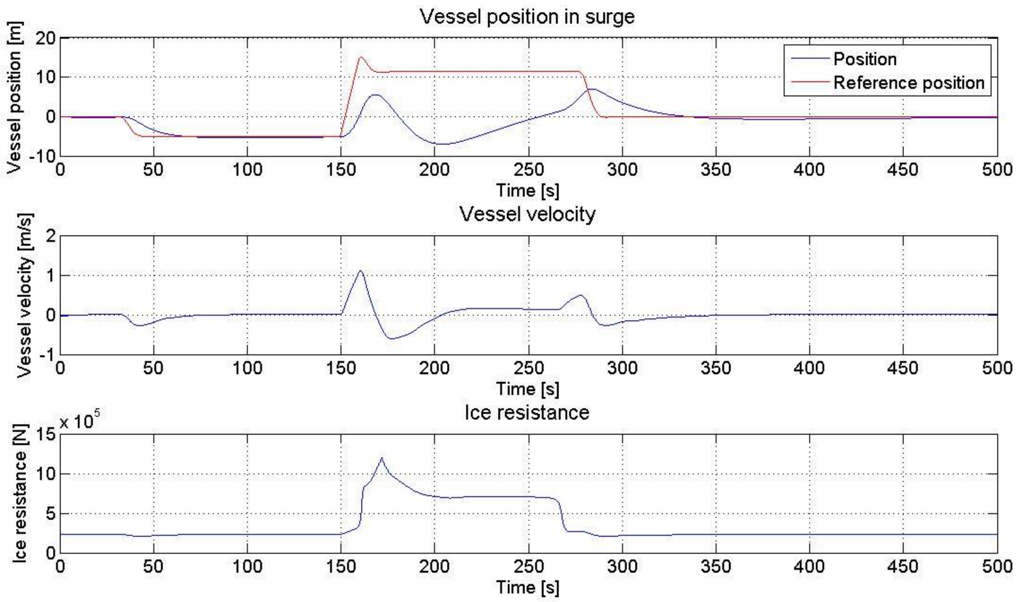


Figure 11.13 Simulation 8: Performance of a DP-system using tactic 4

Figure 11.14 shows the total thrust and the proportional, derivative and integral effect. The jumps in the thrust are caused by change of reference values and by resetting of the integral effect as explained previous in this chapter.

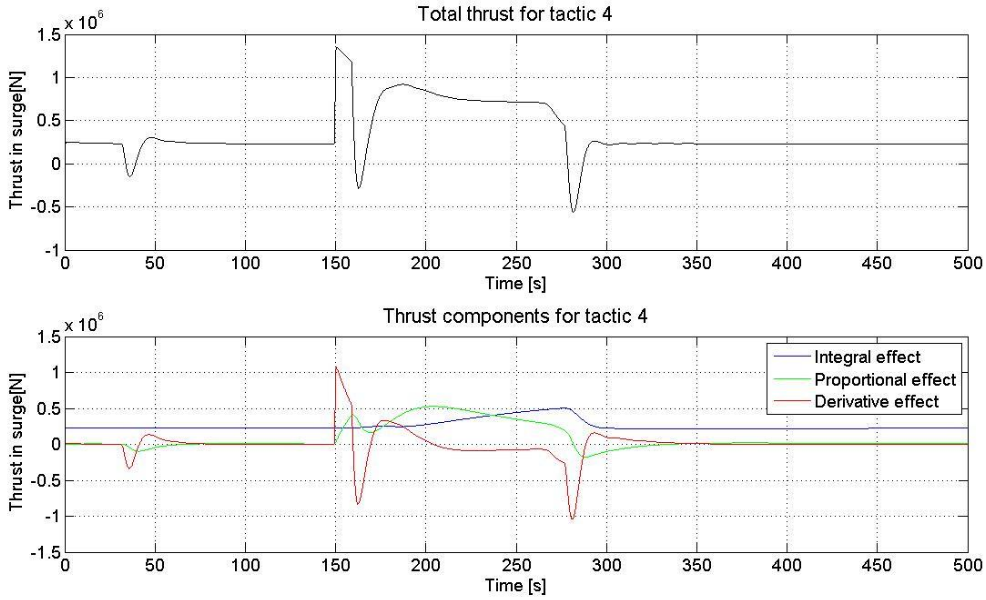


**Figure 11.14 Simulation 8: Controller action for tactic 4 in level ice and ice ridge**

As the velocity for tactic 4 is higher before impact than for tactic 3 it is reasonable to assume that the risk of getting an overshoot when encountering a small ice ridge is present.

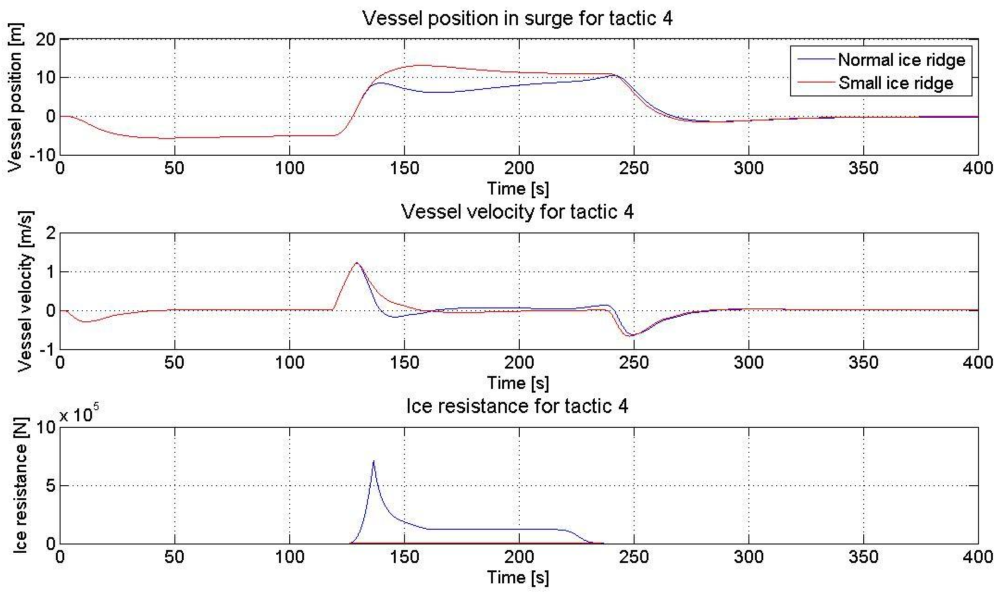


**Figure 11.15 Simulation 9: Tactic 4 when the ice ridge is smaller than expected**

As for tactic 3 the overshoot is not large but could pose a threat to a vessel already operating on the limits of allowed motion.

### 11.2.7 Tactic 5

Tactic 5 does not consider the different zones as explained in chapter 0. Tactic 5 is a pure ice ridge penetration tactic. The tactic is only enabled when the DP-system detects that the vessel is stuck. When the vessel is stuck tactic 5 will automatically initiate a reversed vessel motion followed by a forward full speed maneuver in order to ram the ice ridge. The procedure is repeated until the ice ridge is penetrated.

Figure 11.16 shows the vessel position development when vessel is stuck in an ice ridge and switches to tactic 5.

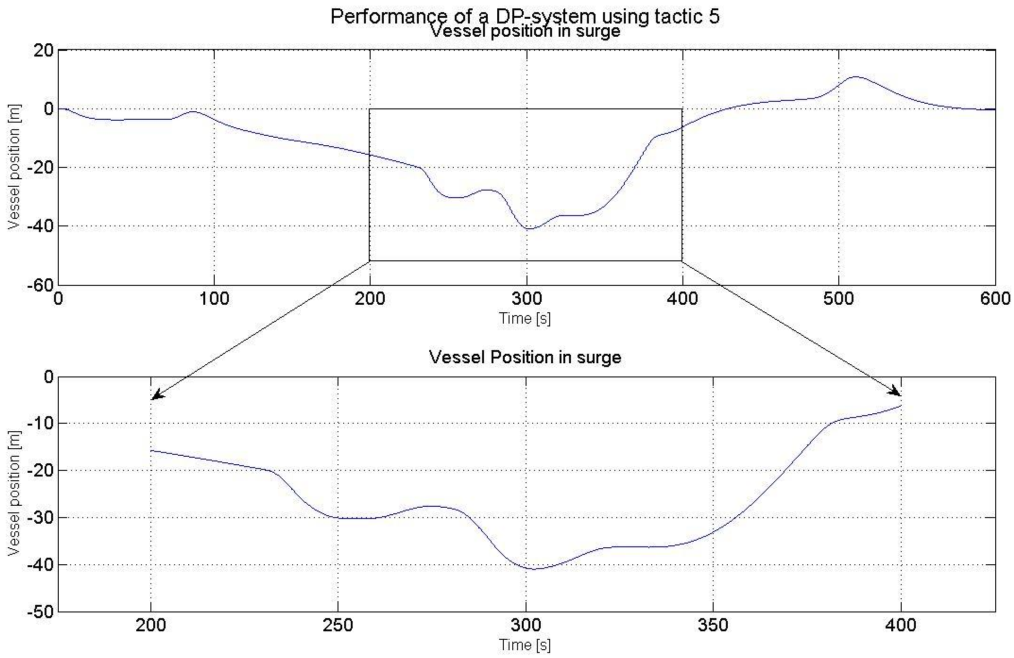


Figure 11.16 Simulation 10: Tactic 5 applied for a vessel that is stuck in an ice ridge

Simulation 10, which is shown in Figure 11.16 above, is based on a vessel using tactic 4 in order to maintain station keeping. In accordance with tactic 4 the vessel initiates a reversed motion when the ice ridge is detected in order hit the ice ridge with a forward motion. However, the ice ridge is not penetrated and forces the vessel in a backward motion with the ice drift velocity.  After about 200 seconds the DP-system detects that the vessel is stuck and tactic 5 is enabled. The events caused by tactic 5 is within the rectangular area and shown in the lower subplot.

The vessel reverses in order to get out of the drifting ice ridge. This incident can be seen in the first bump in the rectangular area. After reversing the vessel initiates a forward motion to ram the ice ridge. The first try was unsuccessful and the procedure repeated. As shown in the figure above full ice ridge penetration is performed after the second attempt.

## 11.3 Discussion and comparison of the different methods

The performance of DP-system exposed to collision with an ice ridge has in this chapter been simulated. Five different ice crushing tactics have been tested and compared to the traditional open water DP-system.

Figure 11.17 below compares the performance of a traditional open water DP-system with the performance of a DP-system using tactic 2. Both tactics are used in a DP-system for a simulated collision between a vessel in station keeping mode and a drifting ice ridge frozen into level ice. As illustrated below the shape of the two graphs are the same. The different is that Tactic 2 has already stationed the vessel 10 meters ahead of the initial reference position at the time of impact. After ice ridge penetration the graph representing tactic 0 experience a larger overshoot than the one using Tactic 2. This property can be explained with the integrator effect that has built up during the position offset. The integrator will move the vessel forward after the ridge is penetrated. For Tactic 2 the integrator value is reset after ice ridge penetration and the overshoot is limited.


**Figure 11.17 Comparing the position offset for DP-system using tactic 0 and tactic 2**

Tactic 2 is a simple tactic. The total distance pushed backwards after ice ridge collision is the same for both situations. However in some situations Tactic 2 will provide a big advantage. If the ice ridge direction is known, it might be preferable to change the reference position towards the ice ridge to compensate for the distance the collision will push the vessel back.

Tactic 1, tactic 3 and tactic 4 are based on the same principles. Generating a forward thrust before the ice ridge impact. Figure 11.18 below presents the positions in surge direction of vessel colliding with an ice ridge during station keeping. As the figure illustrates, all tactics are effective in terms of reducing the pushback distance. Tactic 3 and tactic 4 is although far more complicating, relying on accurate ice ridge velocity measurements in order to maintain a maximum momentum at the time of impact. Tactic 4 has all the same features as tactic 3 but will in addition initiates a reversed motion before ice ridge collision in order to create an even larger momentum. As shown in the figure below tactic 4 will provide the best station keeping abilities.

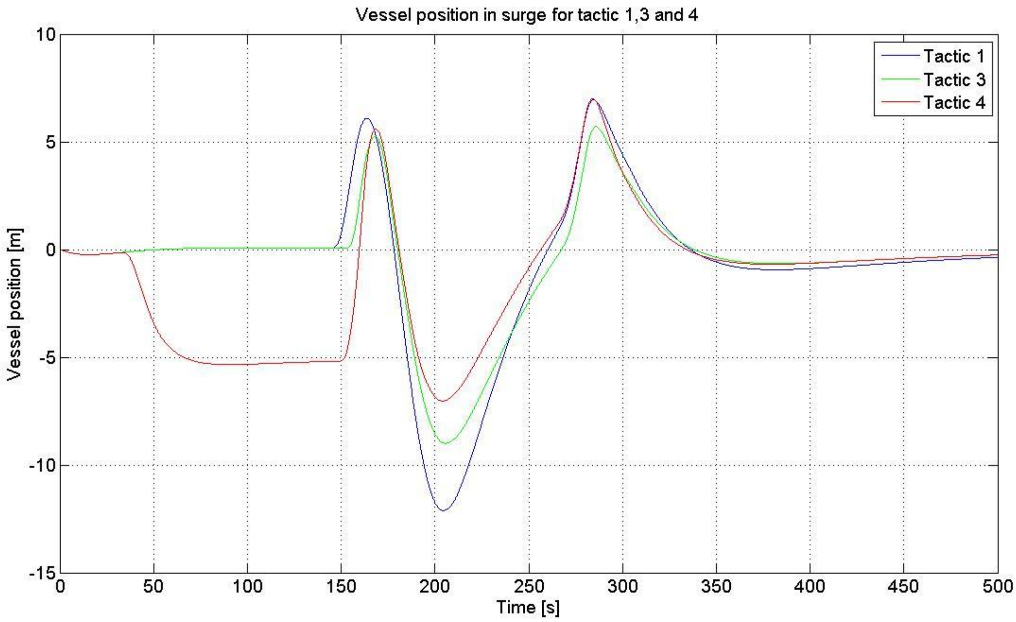


**Figure 11.18 Comparing the position offset of DP-system using tactic 1 and tactic 3**

Table 11.5 presents the position offset results obtained by use of the different tactics. By using the traditional open water DP-controller the maximum position offset is about 21 meters. The simulation results indicates that the performance can be significantly improved by using ice ridge

| Results | | | | |
|---|---|---|---|---|
| **Tactic** | **Ice Regime** | **Forward offset** | **Backward offset** | **Max Offset** |
| Tactic 0 | Level ice with ice ridge | 5 [m] | 21 [m] | -21 [m] |
| Tactic 1 | Level ice with ice ridge | 8 [m] | 11 [m] | -11 [m] |
| Tactic 2 | Level ice with ice ridge | 11 [m] | 9 [m] | 11 [m] |
| Tactic 3 | Level ice with ice ridge | 5 [m] | 9 [m] | -9 [m] |
| Tactic 4 | Level ice with ice ridge | 7 [m] | 6 [m] | 7 [m] |

**Table 11.5 Simulation results**

Table 11.6 sums up some of the benefits and drawbacks of the different tactics.

| **Tactic evaluation** | | |
|---|---|---|
| **Tactic** | **Benefit** | **Drawback** |
| Tactic 1 | Forward momentum | Risk of overshooting |
| Tactic 2 | No overshoot risk, simple tactic | No forward momentum |
| Tactic 3 | Forward momentum, good ice breaking ability | Risk of overshooting |
| Tactic 4 | Larges momentum, biggest ice breaking capabilities | Risk of overshooting |
| Tactic 5 | Break through large ice ridges | Does not consider zones |

Table 11.6 Summary of the tactics

**Tactic 1** initiates a forward momentum in the opposite direction of the ice ridge velocity. The forward momentum will prevent the vessel from being push back by the ice ridge. A forward momentum will introduce a risk of overshooting, i.e. the vessel is penetrating the ice ridge and continues to move forward and exceeds the allow distance of motion.

**Tactic 2** does not introduce a risk of overshoot as it has no forward momentum at the time of impact. As a vessel is expected to be pushed back when it is hit by an ice ridge, tactic 2 initiates station keeping ahead of the desired position pre-collision and will compensate the pushback distance caused by the ice ridge.

**Tactic 3** is accounting for the ice ridge distance and velocity in order to hit the ridge within the allowed radius of motion with a maximum forward momentum. This feature will improve the vessels ice breaking abilities but at the same time provide a risk of overshoot.

**Tactic 4** is based on the same logic as tactic 3 but is initiating a backward motion in order to get more distance to build up a forward momentum before the ice ridge collision. As tactic 4 provides a larger forward vessel velocity it will also introduce an even larger risk of overshoot.

**Tactic 5** is automatically enabled when the vessel is stuck in an ice ridge. Simulations showed that tactic 5 gave the vessel ice breaking capabilities that are larger than for any other tactic.

# 12 Conclusion and recommendations

This section summarizes the results obtained in this master thesis, and proposes areas that need further investigation and analysis. Two simulation studies have been performed in this thesis. First, the simulations were done in order to evaluate the ice ridge model. Secondly and foremost different DP-tactics for station keeping in arctic environment have been evaluated.

## 12.1 Conclusion

### 12.1.1 The ice ridge model

The project thesis “Modeling and calculation of resistance for marine vessels interacting with ice ridges” investigated the interaction between a marine vessel and an ice ridge. The thesis is separated into two parts. In the first part theory regarding the ice ridges and methods of load prediction was presented and in the second part a numerical response analysis was performed.

In chapter 0 a method for ridge resistance calculations was presented. This method was implemented to the MATLAB routine in MCSim as shown in chapter 6. The routine provided stepwise ridge resistance calculations, which showed how the ridge resistance on a marine vessel developed from initial impact to full penetration of the ice ridge. Finally several simulations wore performed in order to investigate how the ridge resistance depended on various parameters.

The basis for the ridge resistance calculation was the Malcom Mellors`s (1980) formulas, which initially wore proposed with regard to investigate the resistance for a ship interacting with thick brash ice. However, the mechanic properties of a first year ice ridge without a consolidated layer are very comparable to brash ice. The total resistance distribution was a result of equation 5.21 combined with the resistance distribution curve. This was developed through iteration where reflections regarding the total resistance equation (5.25), ridge geometry and vessel shape was made.

As discussed in chapter 0 and chapter 0 it was found necessary to include level ice calculations in the ice ridge model for two reasons. Firstly because an ice ridge can commonly be found frozen into level ice and secondly due to the fact that the consolidated layer of the ice ridge can be modeled as level ice. The level ice resistance calculations are based on Eskil Stensønes Røset master thesis from 2009 but with one simplification in order to achieve a faster simulation time.

The ice resistance models presented a brief overview of the total ice resistance force. The resistance was calculated for every time step where there was detected vessel-ice ridge contact. This is a property which enabled the simulator to be used in simulations where a DP-system or a control system is involved.

Simulations of a vessel penetrating an ice ridge were performed in order to investigate the ice ridge model. The result of these simulations wore as predicted in chapter 0. A parameter study was also performed in order to investigate the robustness of the ice ridge model. The results from the parameter study wore as expected. Although the ice ridge model is of a simple nature and has some limitations, the simulations performed in this master thesis have showed that the model provide reasonable results and could be used in DP-system simulations.

### 12.1.2 The DP-system

In chapter 11 simulations of a vessel operating in open water and in the present of level ice and ice ridge were performed. The vessel was subjected to both trajectory following and station keeping in the simulations. For the open water simulation the vessel was exposed to wind and current forces. A DP-system designed to deal with open water conditions was used in the simulation. The performance was satisfactory, the DP-system managed to maintain station keeping and to move from one set point to another.

Although the open water DP-system performed well in station keeping simulations it did not offer optimal results when exposed to ice resistance. Slow dynamics of the controller allowed the vessel to drift off before the integral action was able to compensate for the ice resistance forces.

Several special purpose DP-systems for use in arctic environment have been proposed in this thesis. The special purpose DP-systems wore generated by modifying the open water DP-system as described in chapter 0. The DP-system was fed with detailed information about the incoming ice regime. Using the ice resistance data, optimal reference positions could then be decided.

In order to evaluate the DP-tactics, several simulations wore performed. The ice ridge model presented in chapter 0 represented the ice resistance forces in the simulations. In order to evaluate the performance of the different DP-tactics it was necessary to compare the results with an open water DP-system. The result from the simulation of the open water DP-system exposed to ice forces was used as reference when the different tactics were evaluated.

All of the different DP-tactics wore tested through simulations of encounters with an ice ridge frozen into level ice. Results from the simulation study indicated that the special purpose control strategy provided superior performance compared to the traditional open-water controller. Drift-off subsequent to the vessel-ice impact was shown to be significantly reduced by using the special purposes DP-tactics presented in this thesis. However, the tactics proven to possess the best station keeping abilities were proven to be the ones most vulnerable to overshoot.

It can be concluded that special purpose DP-systems should be considered for station keeping in arctic environment. Five different tactics for ice ridge encountering wore presented, and all performed improved station keeping abilities compared to the open water DP-system.

## 12.2 Recommendation for further work

When dealing with ice properties, modeling of an ice ridge and computer simulations, there seems are no absolute answers or exact science to verify the results. In the process of working with this thesis assumptions and simplifications wore made. The resulting ice ridge model is an attempt to capture the essential elements of the ridge physics rather than a detailed mathematical model. The main challenges and areas of uncertainties for this thesis are presented in this subsection.

All the simulation results in this thesis are based on the assumption that the MCSim provides realistic environmental disturbances and that the vessel dynamics are correct. The MCSim should be further investigated, validated and developed.

The ice ridge model is simple analytical model which only contains the main elements of the ice ridge geometry and strength. The model should be developed further to give a more detailed description of the ice ridge and verified through physical experiments. The ice ridge model is a 3-DOF model. The model should be expanded to excite forces in 6-DOF in order to perform more realistically simulations.

The special purpose DP-system is based on different tactics as described in chapter 0. Some of the tactics rely on detailed information regarding ice ridge size, velocity and porosity. To obtain this information an advanced sensor system is absolute necessary in order to use the DP-tactics in a real world system. An advanced sensory system with adequate redundancy together with signal quality checking, voting and weighting should be included in a special purpose DP-system.

The DP-system is based on full state-feedback. For use in a real-world system an observer should be made in order to estimate the proper states.

Only a few basic tactics for station keeping in arctic environment is presented in this thesis. There are many other features that should be included in a DP-system. Automatic collision avoidance of drifting ice bergs is one example. More DP-tactics could be implemented as well.

Many of the simulations parameters and environmental conditions have to be altered inside the MATLAB M-files and some inside the SIMULINK-model. A more user friendly interface should be created in order to easily access and change the desired parameters and environmental conditions for simulation purposes.

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# Appendix

## A: Choosing parameters

Set of reference parameters is given in the Table, below.

| Name | Abbreviation | Value | Unit | MATLAB variable name |
|---|---|---|---|---|
| Acceleration of gravity | g | 9.81 | $m/s^2$ | g_ir |
| Density of water | $\rho_w$ | 1025 | $kg/m^3$ | rhowater_ir |
| Difference between water and ice density | $\delta_p$ | 108.3 | $kg/m^3$ | delta_rho |
| Density of ice ridge | $\rho_{ice}$ | 916.7 | $kg/m^3$ | rhoice_ir |
| Vessel breadth | B | 17.4 | m | Par_vessel.b |
| Perpendicular length | LPP | 80 | m | Par_vessel.l |
| Length of the bow | $L_{bow}$ | 20 | m | L_bow_ir |
| Length of the mid body | $L_{midbody}$ | 60 | m | L_midbody_ir |
| Vessel draught | $T_d$ | 5.6 | m | Par.Vessel.Shape.T |
| Stem angle | $\alpha$ | 24 | ° | Par.Vessel.Shape.stemangbow |
| Waterline angle | $\beta'$ | 22 | ° | beta |
| Horizontal bow angle | $\beta$ | 30 | ° | beta_ir |
| Internal friction angle | $\phi$ | 50 | ° | phi_ir |
| Porosity of ice | $\eta$ | 0.36 | - | ny_ir |
| Efficient friction coefficient | $\mu_e$ | 0.2 | - | my_ir |
| Plough coefficient | h2/h1 | 4 | - | h2_to_h1_ir |
| Mid body friction coefficient | N | 0.5 | - | N_ir |
| Flexural strength of the ice | $\sigma_f$ | $6x10^5$ | $N/m^2$ | Par.Ice.sigma_f |

Table, Appendix, Reference parameters

## B: Explaining the SIMULINK model

In the attached CD, the SIMULINK model is available. List of contribution done in SIMULINK with relation to this thesis are:

- Ice ridge block, containing both ice ridge and level ice loads calculations
- Vessel control block
- All that are done inside vessel module, except vessel dynamics and simplified thruster dynamics

Inside the created blocks, there are several embedded MATLAB functions and SIMULINK operators. To make it more easy-to-follow, the color on each block tells something about which the type of block it is. The blocks have the following color codes:

- Green, a input
- Red, a output
- Yellow, an embedded MATLAB function
- Light blue, a subsystem
- Gray, summation block
- Light yellow, controller

Additionally, every embedded function has a header containing name of the function, purpose, inputs, outputs, creator and time of last modification.

# C: Control systems values

## C1 Controller

LQ controller gain matrices used in the simulations are listed under.

$$G_p = \begin{bmatrix} 2.86e4 & 0 & 0 \\ 0 & 4.66e4 & 1.14e6 \\ 0 & -2.55e4 & 3.72e6 \end{bmatrix}$$

$$G_i = \begin{bmatrix} 2.00e2 & 0 & 0 \\ 0 & 6.7e2 & 2.46e3 \\ 0 & -2.25e2 & 1.47e4 \end{bmatrix}$$

$$G_d = \begin{bmatrix} 5.40e5 & 0 & 0 \\ 0 & 1.07e6 & 1.74e7 \\ 0 & -4.10e5 & 1.14e8 \end{bmatrix}$$

## C2 Reference model

Damping constant used in the simulations for surge, sway and heading are all the same, with a numerical value of 0.7. Or on a more formal form written as

$$\varsigma_i = 0.7 \qquad (i = 1, 2, 3)$$

The time periods used in the reference model for surge, sway and heading are respectively

$$\mathrm{T}_1 = 15 \text{ sec},$$

$$\mathrm{T}_1 = 15 \text{ sec},$$

$$\mathrm{T}_3 = 10 \text{ sec}.$$