DELFT UNIVERSITY OF TECHNOLOGY

MASTER'S THESIS

Developing a new hull design for the tenders of 'het Loodswezen' to improve the seakeeping behaviour

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Developing a new hull design for the tenders of 'het Loodswezen' to improve the seakeeping behaviour

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Preface

This Master's Thesis marks the end of my academic journey at the TU Delft, more in particular my Master's program in Marine Technology. Over the past year, I have had the privilege of working on a project that combines an innovative design with a practical application: developing a new hull design for the future tenders of 'het Loodswezen', with the primary goal of enhancing comfort onboard. This research has not only expanded my technical expertise, but also provided valuable experience in collaborating with industry professionals.

The project was undertaken at the request of 'het Loodswezen' and I am deeply grateful to Annebel de Deugd and Pim Keijzer for their guidance and insights into the operations and environment of their organisation. I extend my sincere thanks to my supervisor, Jaap Gelling, for his continuous feedback and support, as well as to Peter de Vos, chairman of the graduation committee. A special acknowledgment goes to Albert Rijkens for his patience, support and expertise, which helped me in overcoming the challenges of using Fastship. I am also thankful to Damen for the consultations and providing the designs of the Stan Pilot 2205 and Concept 2 of the KNRM. Finally, I wish to express my gratitude to my family for their unwavering support and encouragement throughout this journey.

Louis Van Cauwenberghe,
Delft, January 2025

Summary

For many years, ’het Loodswezen’ has relied on its tenders to transfer pilots to and from cargo vessels, with the primary focus on ensuring safety of both crew and pilots. In response to evolving emissions regulations and industry developments, the organisation launched the ’Tender of the future’ project. This initiative also provided an opportunity to enhance safety and comfort by redesigning the hulls of their tenders to address slamming, a significant issue observed in the latest tenders, the M-class. This challenge shaped the objective of this Master’s Thesis: "Delivering a new hull design for the tenders of ’het Loodswezen’ which will reduce the vertical accelerations caused by waves compared to the currently used L- and M-class tenders."

The first sub-question towards achieving the main objective is: "Which width is the optimal trade-off between a safe and efficient mode of operation and a high L/B-ratio?" This question was explored from two perspectives. From a safety standpoint, it involved examining the expertise of ’het Loodswezen’, relevant regulations, literature and consultations with Damen to identify the narrowest width that still ensures safety. From a practical perspective, simulations were conducted using Fastship (a tool designed for evaluating vertical accelerations of vessels by analysing cross-sections as falling wedges in the early design stages). These simulations were used to assess the impact of varying widths, achieved by scaling the Stan Pilot 2205, on vertical accelerations. The combined results of these analyses identified the optimal breadth for a tender of ’het Loodswezen’ as 6.46 metres, a design that reduces the vertical accelerations with 10% compared to current tenders while maintaining safe and efficient operations.

In the subsequent phase, the bow and overall hull design were iteratively refined from a standardised planing hull towards the optimal design concept for a pilot tender of ’het Loodswezen’. Many iterations were performed and all simulated in Fastship in order to analyse its peak vertical accelerations. These peak values were used to define comfort, as the crew will base their actions on the highest impacts rather than on average vertical accelerations. The main focus of the iterations was on:

- Maintaining the required initial stability.
- Increasing the deadrise angle to 25 degrees.
- Introducing a twist by increasing the deadrise angle toward the bow.
- Implementing a spray rail to enhance hydrodynamic performance by ensuring that the water is separated from the hull.
- Raising the deck at the bow to increase the reserve buoyancy to prevent bow diving.
- Widening the deck at the bow to ensure that the same operational procedures can be applied.

These iterations culminated in the final bow and hull design, optimised for the tenders of ’het Loodswezen’. This design reduces peak vertical accelerations in the bow while maintaining resistance and operational efficiency, achieving a balance between performance and comfort for safe and effective pilot transfers.

Reducing the bow flare and narrowing the bow have proven to positively affect vertical accelerations but introduce potential challenges maintaining efficient operation with the current working methods. To address this issue, the next sub-question was posed: "Can the deck be shaped in such a way that the drawbacks to operational efficiency are minimised while the flare in the bow is significantly reduced?" Through several iterations, a deck design was developed that enhances operational performance without substantially increasing vertical accelerations. This was achieved by incorporating overhangs in strategic locations, enabling the tenders to operate effectively at an angle against cargo vessels.

A prominent feature often discussed in the context of improving confort and reducing emissions is the use of hydrofoils. At the request of ’het Loodswezen’, a study was conducted to evaluate the feasibility of integrating hydrofoils into pilot tenders. Since existing literature primarily focuses on the advantages and disadvantages of hydrofoil for conventional planing vessels, consultations were held with with two specialised companies. Following a comprehensive analysis, it was determined that incorporating hydrofoils would require a total shift in planning and operations and a complete new and lighter tender design. Consequently, it was concluded that the investment is unjustifiable.

A final design was developed that reduces vertical accelerations with 27.8% compared to a standardised planing hull while maintaining operational efficiency and considering resistance. However, the results should be interpreted with caution, as they are based on simulations using a basic version of Fastship with a limited number of input parameters. These simplifications enabled rapid evaluations but inherently affect the precision of the results.

It is important to note that this design represents a conceptual model. Further research and development are required to obtain reliable results for the actual design. For instance, the LCG plays a crucial role in performance but was, for simplicity, aligned with the LCB in this conceptual phase. In subsequent stages, the LCG should be carefully established to positively influence the results. Additionally, the hull fairing remains to be completed, a necessary step for generating a hull shape suitable for resistance calculations in simulations.

With these advancements, a comprehensive simulation can be conducted by Marin, for which budget has already been allocated. This simulation will provide a more accurate comparison of the new design with the existing L- and M-class tenders of 'het Loodswezen', ensuring a robust evaluation of its performance.

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1 Introduction

1.1 Background

For numerous years, 'het Loodswezen' has utilised its tenders to ensure the safe transfer of pilots to large cargo vessels entering Dutch ports. This operation, inherently challenging, prioritises the safety of pilots and therefore, safety and comfort of the pilots and crew was one of the key parameters in the tender designs. However, developments and regulations regarding emissions and the environmental impact of the maritime industry required a fresh and innovative approach for the existing tender designs. In response, the project 'Tender of the Future' was initiated. This initiative explores potential fuels, features and designs for new tenders, as the near future will require entirely new and innovative tenders to meet the emission goals set by 'het Loodswezen' itself and the government's regulations.

As part of this effort, the M-class tender has already been designed, built and taken in operation. This new design is approximately 15 tonnes lighter, which reduces fuel consumption and, consequently, emissions. However, the lighter design has resulted in severe slamming and a reduction of onboard comfort, according to the crew and pilots. Issues such as sickness among crew-members and pilots have emerged. Furthermore, some have even expressed the unwillingness to operate this tenders as the comfort and safety, one of the key fundamentals of 'het Loodswezen', is compromised.

To address these challenges, the opportunity to reevaluate the hull design and create a one has been included in the 'Tender of the Future' project. The aim is to enhance safety and comfort by minimising vertical accelerations and course instability caused by waves during pilot transfers and sailing operations. This will make the sailing experience more comfortable for the crew and pilots. The decision to incorporate such a study into the project has led to the development of this Master's Thesis, which will focus on this subject.

1.2 Research Objective and Subquestions

It became clear that 'het Loodswezen' wants to develop a new hull design for their future tenders and that this hull design should provide more comfort in comparison to the current fleet, in order to ensure safety and comfort during operations. This has led to the following goal of my Master's Thesis: "Delivering a new hull design for the tenders of 'het Loodswezen' which will reduce the vertical accelerations caused by waves compared to the currently used L- and M-class tenders."

To achieve this main goal, different supporting subquestions need to be solved:

- Which width is the optimal trade-off between a safe and efficient mode of operation and a high L/B-ratio?
- To what extend can the bow and hull be modified to reduce peak vertical accelerations, without compromising the current mode of operation?
- What mechanisms or design concepts could be implemented to mitigate the drawbacks of a AXE bow-like hull design?
- Can the deck be shaped in such a way that the drawbacks towards the operational procedure are minimised while the flare in the bow is significantly reduced?

1.3 Content overview

Before diving into these subquestions, three key aspects will be addressed in chapter 3 to provide a foundation towards the optimal hull shape for the 'Tender of the Future' of 'het Loodswezen'. First, an overview of the fundamental principles of the pilot process conducted by 'het Loodswezen' will be presented. This will be followed by a brief review of the current tenders in operation. Finally, feedback from users about the tenders of today will be summarised in order to map which aspects are felt as uncomfortable.

Based on these insights, the initial design constraints will be outlined in chapter 4. These constraints are partly derived from the current operations of 'het Loodswezen', ensuring workability and safety. Additionally, constraints are established to provide a clear framework, narrowing the project's scope and ensuring its completion within the available resources.

Following the discussions in chapter 3 and 4, in which the boundary conditions are drafted and the current tenders and mode of operation have been analysed, the research into the optimal hull shape will begin. This research will be structured around addressing the research questions above related to various aspects of hull design.

Chapter 5 will focus on determining the optimal beam by answering the question: "Which width is the ideal trade-off between a safe and efficient mode of operation and a high L/B-ratio?" To answer this, an analysis will be conducted using Fastship to evaluate the effect of the L/B-ratio on the vertical accelerations in head seas of the SPi 2205. Additionally, insights from Damen and 'het Loodswezen' regarding safe and efficient operations will be incorporated.

In chapter 6, the bow and hull shapes will be developed through an iterative process, with simulations conducted in Fastship to assess the vertical accelerations in head waves and identify opportunities for improvement. The aim is to balance hull performance with operational safety and efficiency by addressing the following questions:

- To what extend can the bow and hull be modified to reduce peak vertical accelerations, without compromising the current mode of operation?
- What mechanisms or design concepts could be implemented to mitigate the drawbacks of a AXE bow-like hull design?

The main objective of this research project is to develop a new hull design that reduces the vertical accelerations in head seas. As a result, the new hull shape will differ significantly from the current tenders. Literature indicates that radical designs, such as those with narrow bows, can effectively achieve these reductions, as explained in chapter 6. However, according to 'het Loodswezen', AXE bow-like hull shapes may have certain drawbacks. They argue that such designs compromise the vessel's ability to sail under an angle during pilot transfers and limit manoeuvrability. Consequently, the research will explore mechanisms to mitigate these challenges.

Chapter 7 will explore the potential of designing the deck in such a way that it will enhance the efficiency of the current mode of operation while reducing the flare in the bow significantly. So, the following question will be addressed: 'Can the deck be shaped in such a way that the drawbacks towards the operational procedure are minimised while the flare in the bow is significantly reduced?'

In chapter 8, a sensitivity study will be performed in order to analyse to what extend the results are influenced by different parameters. This sensitivity study will then be used to evaluate to what extend and how the results can and should be interpreted.

The thesis will be finalised with a conclusion of the final design developed, followed by recommendations for further research to refine and advance the proposed design.

2 Methodology

The primary goal of this research project is to deliver a new hull design for the tenders of 'het Loodswezen' which will reduce the vertical accelerations caused by waves compared to the currently used L- and M-class tenders. Achieving this requires a systematic approach, involving research into various aspects of design and operation. This chapter outlines the method and subquestions that guide the process towards realising this goal.

Understanding 'het Loodswezen' is a crucial first step. Insight into their operations, equipment and specific requirements is obtained through meetings with the Managers of operation (MO's) from the different regions in which they are active. These discussions cover operational areas, pilot transfer methods, feedback on the current tenders and region-specific requirements.

Following this, an analysis of the existing L- and M-class tenders is conducted, focusing on their behaviour in waves and general specifications. This includes consulting a study by Marin and data from the tender database. These findings form the baseline for developing the new design.

Next, boundary conditions are defined to guide the design process and ensure feasibility within the given resources. These include parameters such as wave height limits, vessel dimensions, stability requirements and operational constraints. The boundary conditions are derived from existing tender data, feedback from the MO's and practical research limitations.

The design process begins with an investigation of the L/B-ratio, a key factor influencing vertical accelerations of planing vessels [5]. While the tender's length is fixed at approximately 22 metres, matching the current designs, the width becomes a critical factor to explore. The width impacts both pilot workability and the vessel's seagoing behaviour. Therefore, the question arises: "Which width is the optimal trade-off between a safe and efficient mode of operation and a high L/B-ratio?"

To address this, a base model, the Stan Pilot 2205 from Damen, will be adapted to create designs with varying breadths. These designs will be tested in Fastship to evaluate the relationship between breadth and vertical accelerations in waves. To ensure operational safety and efficiency, insights from literature, internal knowledge of 'het Loodswezen', consultations with Damen and relevant regulations will guide the assessment of whether reducing the current breadth of 6.86 metres would compromise these aspects. This comprehensive analysis will help identify the ideal trade-off for the new tender design.

Another critical factor influencing vertical accelerations is the bow design and in extent the overall hull design. While optimising the bow shape can enhance seagoing behaviour, it may introduce challenges to the current mode of operation. To balance these considerations, the following questions must be addressed:

- To what extend can the bow be modified without compromising the current mode of operation?
- What mechanisms or design concepts could be implemented to mitigate the drawbacks of specific bow design?

The first question will be explored through an iterative process, where each design iteration will be simulated in Fastship and thoroughly analysed to identify the optimal bow configuration. The second question will be addressed through a targeted literature review to uncover viable solutions for minimising potential drawbacks associated with bow design changes.

The bow and, by extension, the hull design may introduce challenges to the operational procedures. One way to address these challenges is through an intelligently crafted deck design, which can facilitate easier handling of the tender during operations. This raises an important question: "Can the deck be shaped in such a way that the drawbacks to operational procedures are minimised while the flare in the bow is significantly reduced?" Answering this will involve balancing the needs of operational functionality with structural and hydrodynamic considerations.

Once all these subquestions have been addressed, the final tender concept will be developed. The final step involves evaluating the results to ensure their reliability and to identify any additional considerations that may need to be provided. This will accomplished by conducting additional simulations. One set of simulations will examine the impact of the LCG on the results, while another set will explore the effects of the limited number of input parameters and the use of a basic version of Fastship.

With all these steps finished, a conclusion can be drawn on whether or not the main objective is achieved. Furthermore, recomendations towards further research can be addressed.

3 Mode of Operation and Current Tenders of 'het Loodswezen'

The introduction indicated that safety of the pilots is of top priority for 'het Loodswezen'. However, this priority is somewhat compromised in the tender designs and specifically in the M-class design, the newest tender of 'het Loodswezen', due to the severe slamming experienced. Therefore, a new hull design is required to reduce the vertical accelerations in head waves. To generate such a design, it is essential to first understand the mode of operation of 'het Loodswezen' and the current tenders they use. This information will be provided in this section.

As outlined in the introduction, the main goal is to develop a new hull design for the tenders of 'het Loodswezen' which will reduce the vertical accelerations in head waves compared to the L- and M-class tenders. While reducing the vertical accelerations is the main focus, several other factors also influence the design. One key factor is the mode of operation, which imposes specific requirements on the design. To gain a better insight in the modus operandi, the MO's were interviewed, as it differs from that in other countries.

The first aspect of the pilot method is quite straightforward. The tender picks up pilots from shore or the P-class vessel, which lies close to the pilot station at sea on which pilots can take a rest, and sails of towards a cargo vessel. Once the cargo ship has adjusted its course and speed as requested, a 'controlled collision' will take place. After this 'collision', the tenders will sag out towards the ladder, where the pilot transfer will occur. Once the pilot has made the transfer, the tender will keep direct contact with the cargo ship under an angle instead of in a parallel way, as in other countries. The main driver of this is the safety of the pilot. If the pilot would fall from the ladder, he will drop in the water instead of on the deck of the tender and therefore the risk on severe injuries or even death is heavily limited.

Next to the pilot method, also basic knowledge of the tenders is usefull information for a new tender design. 'Het Loodswezen' uses five different classes of tenders, the Aquila-, Discovery-, H-, L- and M-class. The M-class is the newest class, with only 2 of the 5 tenders already in operation. The H-class is the only steel tender and propelled with propellers instead of jets. This because this tender is designed for icy conditions. Since the MO's gave most of their feedback on the Discovery-, L- and M-class, these are the only tenders on which extra info was gained. The overall dimensions of these three tenders are given in table 1.

Table 1: Main dimensions of the Discovery-, L- and M-class

	Discovery-class	L-class	M-class
Loa (m)	20.95	22.37	22.8
Lwl (m)	17.53	19.09	20.5
Boa (m)	6.35	6.86	6.86
Bmoulded (m)	5.5	5.86	5.8
Tdesign (m)	1	1.2	1.1
D (m)	2.7	2.87	2.87
Displacement (tons)	37	58.36	49.9

Further research on the tenders was conducted to understand the current experiences and seakeeping behaviour. Meetings with the MO's revealed that the crew overall has negative experiences with the M-class. They claim that more severe slamming occurs when sailing the M-class compared to other tenders. To investigate this, a study into the seakeeping behaviour of the M- and L-class was performed by Marin. Conclusions from Jaap Gelling showed that there was indeed an increase in vertical accelerations, which can be seen in figure 1, and so the concerns of the crew and pilots have been confirmed. In a further stage in this Master's Thesis, the designs will be analysed more closely to understand what causes this difference.

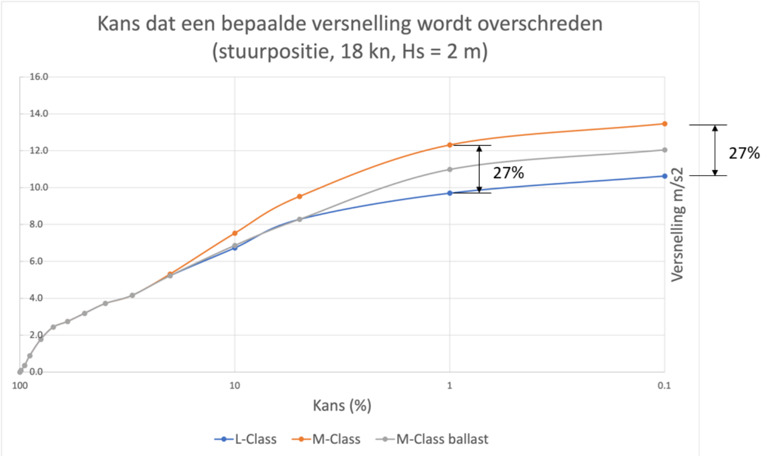


Figure 1: Comparison of the vertical accelerations in head waves

Another interesting aspect was found when evaluating the Discovery-class and more in particular the Enterprise, an adapted version of the Discovery-class. In 2016, this tender was adapted in order to test a new bow design. The actual modification was to attach a new bow over the already existing one, as can be seen in figure 2. This bow was much sharper and added waterline length and weight, but, according to the engine data, managed to reduce the fuel consumption. Furthermore, the seakeeping behaviour of the modified Enterprise is better compared to all other tenders in some of the MO's opinion. The question arises if this is the result of the sharper bow and added weight, but has not been investigated as there were no measurements performed.

Figure 2: Adjusted bow of the Enterprise ([1])

4 Boundary Conditions

When observing vessels entering and departing from ports, a significant diversity in shapes and dimensions can be noticed, reflecting their specific operational purposes. This diversity suggests that developing a new hull design entails making a multitude of decisions among an abundance of existing options. To narrow down these choices, boundary conditions can be established based on the intended function of the vessel. This chapter will elaborate this process for a pilot tender of 'het Loodswezen'.

As discussed earlier in the introduction, the goal of this Master's Thesis is to develop a new hull-design for the tenders of 'het Loodswezen'. Therefore, the purpose of the vessel is to provide safe and quick transfers from shore to cargo ships and vice versa for pilots. This operation goes hand in hand with a specific working method, as explained in the previous chapter, which will set boundary conditions to the design.

From the working method and as repeated already several times, it is crystal-clear that pilot safety is the main priority for 'het Loodswezen'. Therefore, this specific working method should be maintained as it guarantees a safer working environment. In addition, it is not in the scope of the Master's Thesis to develop a new working method which will suit a potential new design. Therefore, the new hull design must not compromise this fundamental working principle of 'het Loodswezen'.

Another important aspect of the pilot process for the new hull design is the required service speed, determined by factors such as pilot schedules, locks, sailing distances, tender availability, and emissions. Various options exist to ensure every cargo ship is provided with a pilot, from longer waiting times to increased tender deployment. However, it was decided to maintain the current service speed of 28 knots for simplicity. Furthermore, the MO's stated that the service speed will drop in heavier seas due to a voluntary speed reduction to reduce the intensity of impacts, for example: to 18 knots at a significant wave height of 2 metres and even to 13 knots at a significant wave height above 2.5 metres. It is decided to include these voluntary speed reductions in the research and therefore the speed at a significant wave height between 2 and 2.5 metres will be set at 18 knots. The primary reason for selecting these service speeds is that a comprehensive study is needed to determine which option would most effectively reduce emissions. For instance, decreasing the service speed could lead to longer waiting times for cargo vessels, increasing emissions, or require more tender deployments, which also increases emissions. The environmental impact of these options must be studied before making an informed decision. As this analysis is beyond the scope of the Master's Thesis, the current service speed was chosen for simplicity. Additionally, maintaining the same service speed ensures a valid comparison between the behaviour in waves of the new hull design and the tenders currently used.

In table 1, the main dimensions of the Discovery-, L- and M-class are depicted and will be used for a next set of boundary conditions. Since a new hull design is required, not all these dimensions will be used as a boundary condition, but only as a reference. However, some dimensions will be set as a boundary condition: the length overall, the displacement and draught. The length overall is constrained by the Koopmanshaven in Vlissingen. In this narrow harbour, the tenders should be able to make a 180-degree turn and therefore the length overall of the current tenders is the maximum length which allows these vessels to execute these manoeuvres. Given this boundary condition, the length overall of the new tender design cannot exceed 22.8 metres. Regarding displacement, this boundary condition is set due to weight considerations. In order to realise a fair comparison between the current tenders in service and the new hull design, a realistic weight for the new hull design should be selected. It is assumed that the weight of the M-class represents the minimum achievable weight for a tender of 'het Loodswezen'. This assumption is based on the explanation from 'het Loodswezen', which claims that only essential systems are installed on the Mira to minimise weight. Therefore the boundary condition concerning the displacement states that the weight of the new tender must equal a displacement of 45 tonnes (Mira without ballast). The final dimension is the draught, which will be held the same as for the M-class as well. The driver behind this decision is conformity, especially in Vlissingen, where they cooperate with the Belgian pilot service. In order to maintain efficient operation, the MO's asked to keep the depth the same.

When analysing a design, one of the first checks that have to be performed is the stability. This will be done by determining the GM of the vessel. In consultation with Jaap Gelling and based on the Stan Pilot 2205, a minimum GM value of 1.5 metres was identified as being required for a pilot tender.

Furthermore, the GM is based on the KG of the vessel. Since only the hull will be designed in this thesis and no mechanisms or systems will be implemented, the KG cannot be determined accurately. Therefore, the constraint is set to select a CoG(z) of 2.1 metres, which is equal as the CoG(z) of the Mira.

A last aspect of the stability is the CoG(x). For the same reason as the CoG(z), it is impossible to determine the CoG(x). Therefore, the CoG(x) will be set equal to the CoB(x).

A final set of boundary conditions is based on the weather conditions in which the tender will sail. These conditions should be set during the design phase, as the design will be tested in only a few scenario's in order to speed up the testing process and as a result the design phase. These conditions are not picked randomly, but are based on a previous evaluation of the M- and L-class tender. The average conditions, as described by Lex Keuning [6], of sea state 4 are selected to be the conditions in which the preliminary designs will be tested and are presented below:

- T_p = 6s, $H_{1/3}$ = 2.25m and a forward vessel speed of 18 knots

By developing these boundary conditions, the options for the hull-design have been narrowed down and it should be possible to develop specified for a pilot tender of 'het Loodswezen'.

5 Width of the Vessel

A first parameter that needs to be set is the width of the vessel. There are several aspects which could determine the breadth of a vessel. In this chapter, the most important ones will be discussed and there influence will be examined and clarified.

5.1 Width determination based on literature, principles and findings of 'het Loodswezen'

First of all, a closer look towards the beam of the current tenders has been taken. This was done by reviewing datasheets from the tenders and by interviewing the MO's, as stated earlier. The datasheets showed that the width overall of the Aquila-, L- and M-class tenders is uniformly around 6.8m. In contrast, the width of the Discovery class is somewhat smaller and equals 6.35m, as can be seen in table 1. More info about these numbers was provided by the MO's. Apparently, the principal idea behind these uniform dimensions is that it would make operating with different tenders easier for the crew.

The MO's claimed that more severe slamming was experienced with the M-class, which was also confirmed by Marin, as stated in chapter 3. Analysing the designs of the different tenders more closely and discussing these findings with the MO's with the data presented in figure 1 in mind helped understanding these differences in vertical accelerations. The main reason behind this difference is the increase of flare above the second spray rail of the M-class. A comparison of the designs of the L- and M-class is provided in figure 3, in which the blue circle clearly indicates the flare difference. Although the hull was designed to reduce vertical accelerations, the requirement to set the width at 6.8 meters and maintain the same deck circumference led to this flare increase, thus counteracting this effect. By this, it could be stated that reducing the flare (and to extent the width) of the M-class could have a positive effect on slamming. This is in line with the findings of the MO's, which is that the smaller Discovery-class tender offers more comfort in waves compared to the wider M- and L-class.

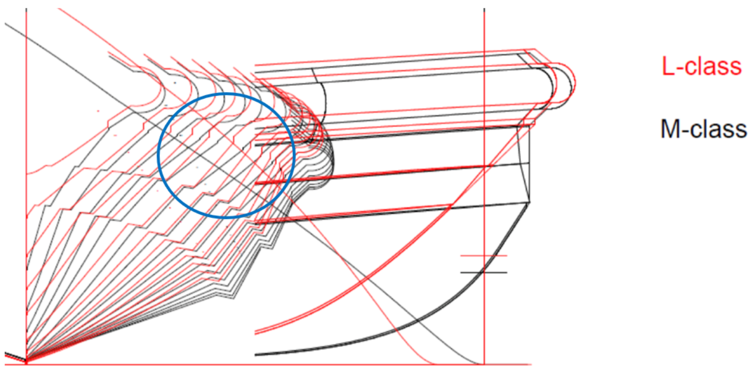


Figure 3: Comparison of the designs of the L- and M-class

However, the conclusion drawn above to reduce the width of the tender is solely based on the interpretation of the data presented by Marin and the opinions of the MO's. For this reason, studies and literature were used to examine if these opinions could be substantiated.

Literature about the Delft Systematic Deadrise series (a database of planing hull forms which has led to a new and rapid assessment method for the hydrodynamic performance of planing boats using speed independent polynomial expressions for resistance, sinkage and trim) showed two main conclusions concerning the seakeeping behaviour of fast planing hulls:

- First, a higher deadrise angle results in better seakeeping, with a small paid penalty on the resistance in case of a high L/B-ratio [7].
- Second, a high L/B-ratio also enhances seakeeping [5].

The importance of a high L/B-ratio was not only emphasised in this literature but also in studies of the enlarged ship concept. The primary principle of the enlarged ship concept is to select a ship, which already meets the customer requirements, as a starting point and lengthen it forward of the accommodation while keeping all the other dimensions the same. The idea behind this is to increase the L/B-ratio and to move the accommodation relatively more aft [8].

Based on these studies, it is evident that increasing the L/B-ratio will indeed improve the seakeeping behaviour of the tenders. However, given the boundary condition that the vessel's length overall cannot exceed 22.8 metres, the potential to increase the L/B-ratio by lengthening the waterline is very limited. Consequently, the increase of the L/B-ratio will be achieved by reducing the width of the tender. Due to this, an important note regarding the effect of the enlarged ship concept has to be made. It was already mentioned that the main idea of this concept is to lengthen a ship in order to move the wheelhouse more aft and increase the L/B-ratio. However, because of the length restriction mentioned, the wheelhouse will not be relocated relatively more aft. Therefore, one of the key benefits of the enlarged ship concept to reduce the vertical accelerations experienced by the crew is lost.

Another parameter that influences the width of the tender is safe operation. As explained before, the tenders of 'het Loodswezen' are utilised to ensure safe transfer of pilots to cargo vessels entering and leaving Dutch ports. During this operation safety of the pilots is prioritised. For this reason, each design parameter has to be evaluated from this point of view as well. Taking into account this parameter, the MO's have indicated that the width of the gangways is an important factor. This because the wide gangways will prevent crew and pilots from being trapped between the deckhouse and the hull of the cargo vessel in rough seas. It is straightforward to assume the same width for the new tender design as for the L- and M-class, as it is agreed within 'het Loodswezen' that the gangways are wide enough. However, another aspect of the safety of the pilots is the vertical accelerations experienced by them and the crew. From literature, it became clear that reducing the width of the tenders will lead to a reduction of the vertical accelerations and therefore increases safe operation. As a result, further research was conducted in order to find the minimal width of the gangways which still ensures safe operation.

In table 1, it can be noticed that the breath overall of the Discovery-class is 0.5m smaller than the L- or M-class, the breadth overall is respectively 6.35m and 6.86m. It should be figured out by what a width difference is. A closer look at the design plans of both the L-class and Discovery-class brings up a first difference. The gangways of the Discovery-class are 0.85m wide and even 0.62m at the smallest point with the stairs, as can be seen in figure 4. The gangway of the L-class on the other hand has a width of 1m. Another difference can be found in the width of the gangway in the wheelhouse between the chairs of the passengers, which is respectively 1m and 0.8m for the L- and Discovery-class. These differences only affect the passengers and crew, but on the other hand, also the engine room and wheelhouse is smaller and therefore, space difference between engines, electronic devices etc. will be different as well.

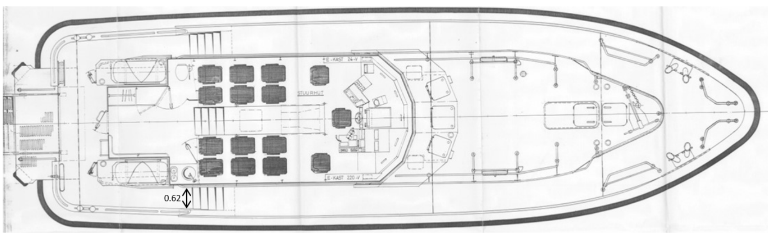


Figure 4: Top view of the main deck of the Discovery class

The main take away is to evaluate if a pilot tender could be made more slender without compromising safe operation. Since some MO's indicated that the Discovery class was preferred and no shortcomings were mentioned about the gangways, the conclusion can be drawn that the gangways could be made at least 15cm smaller and the gangway in the wheelhouse at least 20cm smaller.

This is solely based on the tenders of 'het Loodswezen' and the findings of crew and pilots. It is evident that checking if the gangways are wide enough for safe and efficient operation is quite a subjective given. However, it is still possible to check this opinion and generate more information about these parameters in order to be able to form a more global based conclusion about this. Therefore, Damen was consulted. They design and build pilot tenders for customers all over the world and have a better inside in what is found safe and efficient in comparison with 'het Loodswezen', as their opinion is solely based on their experience with their own tenders and dutch pilots.

After consulting Damen, a better insight in the width of the gangways was provided. First of all, it should be noted that there are no (inter)national regulations concerning the width of the gangways of pilot tenders. It is up to designers, builders and pilot institutions to determine the width of the gangways. Damen always consults their clients in order to gain their requirements about the width of the gangways, which is generally determined by the crew and pilots operating the tender. Overall, according to Damen, pilots require a minimum width of 0.9 metres.

Considering safe and efficient operation based on findings of 'het Loodswezen', literature and consultations of Damen, the conclusion can be drawn that a width of the gangways equal to 0.9 metres is more than sufficient. In consultation with 'het Loodswezen' this width could even be reduced and set at 0.85 metres, which equals the width of the gangways of the Discovery-class. For now, taken a width of 0.9 metres and reducing the width of the gangway in the wheelhouse with 20 cm, the minimum breadth overall of a pilot tender for safe and efficient operation equals 6.46 metres.

5.2 Effect of L/B-ratio on the vertical accelerations of Pilot Tenders

In the previous section, a minimum beam for safe and efficient operation was set based on literature and findings of 'het Loodswezen'. This consideration of safe and efficient operation included vertical accelerations, which is the main driver of the new hull design. However, the literature used to analyse these accelerations focused on fast planing vessels rather than the specific pilot tenders. Therefore, additional research will be performed to assess the actual impact of the L/B-ratio on a 22-metre pilot tender by varying the vessel's breadth overall. This research will be elaborated more in this section.

5.2.1 Set-up

Since the design is still in its early stages, a new hull design has not yet been developed. Therefore, a base vessel will be used in Fastship to determine the optimal beam for the new tender design. The selected base vessel is the Stan pilot 2205 from Damen, depicted in figure 5 with its main dimensions provided in 2.

To evaluate the effect of the L/B-ratio on the seakeeping behaviour of a pilot tender, the beam of the Stan Pilot will be varied. The current tenders will serve as a reference, resulting in adjustments of the width to 6.86 and 6.46 metres. These values correspond to the B_{oa} of the M-class and to the minimum B_{oa} determined as necessary for safe and efficient operation in section 5.1 respectively. However, research on the Discovery-class suggests that further width reduction may be possible. To investigate this, the SPi 2205 will also be analysed with its original width of 6.1 metres.

This analysis aims to assess whether reducing the width to 6.1 metres significantly affects vertical accelerations and whether consultation with 'het Loodswezen' is required to consider its feasibility. Additionally, the study will evaluate whether there is a notable difference in seakeeping behaviour between tenders with widths of 6.86 and 6.46 metres.

Figure 5: Stan Pilot 2205

Table 2: Main dimensions SPi 2205

Loa (m)	Boa (m)	Tdesign (m)	D (m)	Displacement (tons)
22.7	6.1	0.91	2.6	48.43

The width of the tender will not be the only dimension that is varied, as varying only one dimension is not feasible. However, the primary goal is to assess the effect of the L/B-ratio on the vertical accelerations by adapting the tender's width. To maintain the focus on this, most dimensions will remain unchanged. The length overall, deadrise and displacement will be kept constant, while only the depth will be varied along with the width of the vessel to ensure the same displacement. This approach is selected because the length of the new tender design is constraint at 22.8 metres. Furthermore, increasing the deadrise angle is known to improve the seakeeping behaviour of the vessel ([7]). Since the objective of this part of the research is to analyse the impact of the L/B-ratio on the vertical accelerations by varying the width, adapting the deadrise angle would distort these results, making it impossible to draw accurate conclusions on the impact of the L/B-ratio.

5.2.2 Fastship

In the beginning of this section, it was mentioned that Fastship will be used to analyse the different designs. However, before jumping directly to the results of Fastship, a short introduction of this program, in which the designs will be simulated in head seas in order to analyse the vertical accelerations, will be provided in this section.

Fastship was originally developed by Zarnick (1978) and later extended by Keuning (1994) and was a strip theory based nonlinear mathematical model of the motions of a planing monohull in head seas [9]. However, Van Deyzen (2006) included the possibility to perform simulations in beam seas including roll.

Fastship is based on the dynamics of falling wedges in water. In the model, the vessel is split into cross-sections (described from line 8 to 35 in Appendix A), each modelled as falling wedge with a known behaviour of the force in time starting from an initial falling velocity. Using linearised potential flow theory for waves combined with the instantaneous vertical velocity of the ship now as a model for the falling velocity, allows to determine the force on a section of the ship in waves. Integrating these forces over all sections along the length of the vessel gives the force input for solving a coupled set of equations of motion for the ship in a seaway.

An important assumption in FASTSHIP is that there is no hydrodynamic interaction between sections [10]. And wave forces are not the only forces on the vessel. The ship is afloat and at forward speed the buoyancy force needs to be corrected for the changed pressure distribution over the hull. The correction can only be accounted for in an approximate way and is done by having an input parameter for the corrected buoyancy ($a_b f$).

Forward speed also induces a total lift force on the ship that has to be determined from the geometrical information of the individual sections, again in an approximate way and in the model represented by the added mass coefficient (C_m).

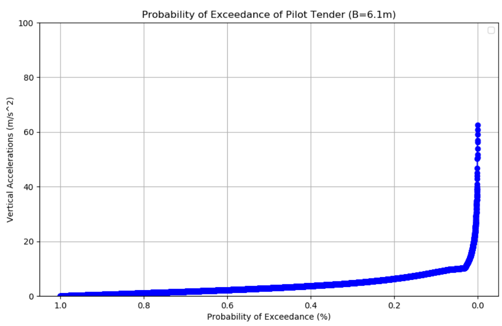
Both remarks show that the $a_b f$ and C_m (2^{nd} and 3^{th} parameter in line 4 of Appendix A) are important input parameters and should be chosen with care [9]. In Fastship these input parameters can also be calculated based on the sinkage and trim of the vessel using a simulation in calm water. This will be done for all the designs discussed in this Master's Thesis.

In order to determine the sinkage and trim of the design in calm water at a certain speed, Planing Hull Form (PHF), developed by L.J. Keuning, J. Gerritsma and P.F. van Terwisga, was used. PHF is a prediction program, based on model tests, to approximate the total resistance, trim and sinking of planing hull forms. It should be noted that the accuracy for determining the sinkage and trim depends on how well the hull under consideration fits within the shape variations that were considered in the experiments and therefore, the results of Fastship could be slighty off.

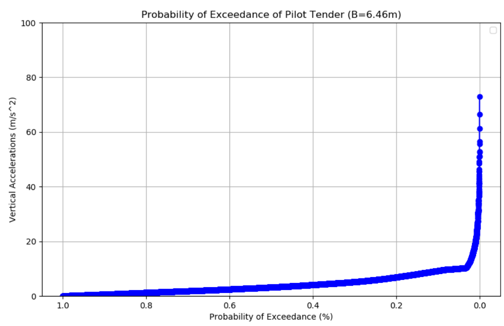
The final important input is the wave spectrum (shown in Appendix B), which is generated using the Jonswap spectrum. This spectrum represents the various sea states of the North Sea. After this input file is uploaded into Fastship, the simulation can be executed and the equations of motions will be solved. The resulting data is then processed, with the probability of exceedance being calculated to asses onboard comfort. This approach is based on the research of Lex Keuning [11], which highlights that peak vertical accelerations and their associated probability of exceedance are the primary factors influencing comfort, rather than the average accelerations, since the crew reacts on the highest impacts. Ultimately, these probability distributions will be used to evaluate the performance of the different design iterations.

5.2.3 Results

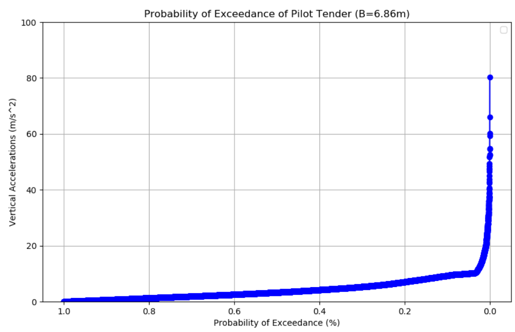
Before analysing the results, it is important to address a specific consideration. As discussed in chapter 5.2.2, the sinkage and trim values were determined using the resistance program developed by the TU Delft, which is based on the DSDS. The DSDS database comprises standard planing hull forms and does not account for the AXE bow featured in the SPi2205. Consequently, the calculated sinkage and trim values for the SPi2205 may exhibit inaccuracies. However, following a detailed evaluation of the results and a consultation with Albert Rijkens, it was determined that these deviations do not pose a problem for the purpose of this comparative width analysis. Since all three designs incorporate the AXE bow, any deviations in sinkage and trim occur uniformly across designs, ensuring that comparative analysis remains valid. Thus, the conclusions derived from these results are considered reliable.



(a) Probability of exceedance for B = 6.1m



(b) Probability of exceedance for B = 6.46m



(c) Probability of exceedance for B = 6.86m

Figure 6: Probability of exceedance of the vertical accelerations for the Damen SPi 2205 with different widths

The results from the Fastship analysis have been processed and the probability of exceedance of the vertical accelerations at the bow is presented in figure 6. The peak vertical accelerations observed are 62.5 m/s^2, 72.9 m/s^2 and 80.5 m/s^2 for widths of 6.1m, 6.46m and 6.86m, respectively. A reduction in the width to 6.46m would result in a decrease of the peak vertical accelerations by 9.44%, while a further reduction to 6.1m would achieve a reduction of 22.36%. Based solely on these results, it can be concluded that minimising the width, in this case to 6.1m, yields the most favourable outcomes. In other words, with the length held constant, the highest L/B-ratio should be selected. This finding aligns with the conclusions of Van den Bosch [5].

5.3 Optimal width of the new tender

After analyzing the findings from literature, regulations, the operational experience of 'het Loodswezen', insights from DAMEN Shipyards and the influence of beam variations on vertical accelerations in pilot tenders, a conclusion can be drawn regarding the optimal beam for the new tender design. The conclusion incorporates the scope of this thesis, reducing the vertical accelerations while ensuring workability and safety.

Literature indicates that the L/B-ratio should be maximised to enhance the seakeeping behaviour [8], [5] and [7]. However, practical considerations such as the space required for machinery and equipment impose limits on how much the beam can be reduced. As discussed, it is possible to slightly narrow the gangways in the wheelhouse and on deck. Based on consultations with Damen, a gangway width of 0.9m is considered as common. In some cases, such as the Discovery-class, gangway widths as narrow as 0.62m have been deemed sufficient. Considering these constraints, the optimal beam for the tender was set at 6.46 metres.

The study conducted using Fastship to evaluate the effect of the L/B-ratio on vertical accelerations confirmed that a higher L/B-ratio significantly reduces peak vertical accelerations. A reduction of up to 22.4% is achievable if the beam is decreased to 6.1m.

However, reducing the width further raised concerns about safety and workability. Narrower gangways could compromise safety during pilot transfers, especially in rough seas. Wide gangways on pilot tenders are critical for protecting crew and pilots from being trapped between the deckhouse of the tender and the hull of a cargo ship. Tragically, such an accident occurred with the Lacerta operated by 'het Loodswezen', resulting in a dead casualty [12]. To prevent similar incidents and ensure the safety of crew and pilots, the gangway width for the new tender has been set at a minimum of 0.9 meters, precluding further reductions in the vessel's beam.

As a result, the optimal beam for the new tender design is established at 6.46 metres. This configuration provides a balance between performance, safety and workability, while achieving an approximate 9.5% reduction in vertical peak accelerations compared to the M- and L-class.

6 Bow Design

Based on the literature research and as it will be elaborated in this chapter, the bow design could play an important role in the seakeeping behaviour of vessels. However, certain bow shapes could influence the operational procedures of 'het Loodswezen' in a negative way. Therefore, ways should be found in order to mitigate the disadvantages of proposed bow configurations. This could involve a specific deck design and incorporation of mechanisms. Overall, a balance must be found in the bow design between reducing the vertical accelerations and limiting the impact of the bow design on the current mode of operation, which will be done in this chapter.

6.1 Proposed bow shape

The statement that there exist hundreds and hundreds of bow shapes, each with their function, purpose, advantages and disadvantages should not be shocking. In the search towards bow shapes which will reduce the vertical accelerations in waves, many concepts popped-up, some more promising than others, with the most promising ones being the enlarged ship concept (ESC) and the Axe bow concept.

The ESC was previously introduced as a concept with the main idea to take a base vessel, which meets the customer's requirements, and lengthen it forward to increase the L/B-ratio and place the wheelhouse relatively more aft [8]. In a further stage of this concept, it was observed that the vertical accelerations could be further reduced with the introduction of bow modifications. These bow modifications were made possible by the void space which is created by lengthening the ship. The main objective of these modifications is to decrease the vertical peak accelerations, as this will enhance the operability of the vessels [11]. To achieve this, extensive research was conducted on the non-linear behaviour of fast planing hulls in head waves. The research revealed that the non-linear Froude-Krilov forces and the hydrodynamic lift forces influenced the non-linear behaviour of the vessel the most. Consequently, to reduce the peak vertical accelerations, these forces should be minimised [6] [13].

The first bow shape modification focused on minimising the non-linear Froude-Krilov force. In short, the Froude-Krylov force is determined by integrating the hydrodynamic pressure in the undisturbed wave over the instantaneous submerged volume of the hull. This leads to formula 1, where $y_w(t)$ represents the instantaneous waterline half beam of the cross section, $A_x(t)$ the instantaneous submerged transverse area of the cross section and ζ the instantaneous wave height. This formula shows that if the Froude-Krylov force has to be minimised, the change in the sectional $y_w(t)$ and $A_x(t)$ has to be minimised when the section is carrying out a vertical displacement with respect to the water surface. Translating this to the geometry of a vessel, means that the flare of the different ship sections has to be reduced, especially in the fore ship. [6]

$$F_{FK} = 2 * \rho * g * \zeta * y_w(t) + \rho * g * KG * A_x(t) \tag{1}$$

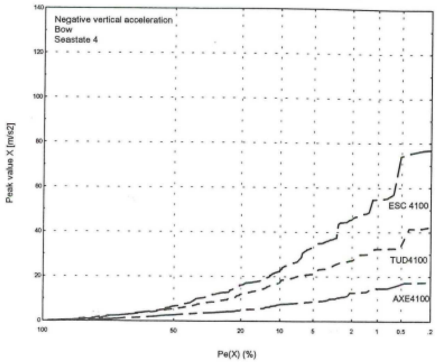
The second aspect that influences the vertical accelerations most is the hydrodynamic lift. These hydrodynamic loads are calculated based on the added mass, which aligns with the slender body theory. According to this theory, the normal force on a transverse section of the hull, can be calculated by determining the rate of change of momentum of the incoming fluid expressed in terms of added mass and the particular cross section under consideration. Based on the analytical and experimental research by Lex Keuning [14], the change in $y_w(t)$ should be minimised, similar to the approach to minimise the Froude-Krilov forces. Keuning argued that the non-linear added mass is much more important for the time dependent magnitude change of these hydrodynamic forces than the frequency dependency of the sectional added mass. Furthermore, since this sectional added mass at high encounter frequencies (fast ship in head waves) may be considered to be proportional to the change in sectional beam $y_w(t)$, it should be minimised. [6]

Figure 7: Render of the fast crew supplier 5009 by Damen ([2])

This has lead to the introduction of the bow modified enlarged ship concept, the TUD4100, as explained earlier. The changes made in the hull shape could be summarized by:

- Reducing the flare of the bow sections
- Narrowing the waterline
- Increasing the waterline length
- Deepening the fore foot
- Increasing the freeboard

These findings could be taken to a far more radical elaboration, which was done with the development of the AXE bow concept [6]. The features of this design are the flare that is minimised to almost zero, the stem that is placed almost vertical to increase the waterline length, increased sheer forward to minimise the risk of green water on deck and guarantee sufficient reserve Buoyancy and lastly, the centreline of the hull has been given a negative slope towards the bow, which can be seen in figure 7. Compared to the ESC 4100, great care has been given to maintain a comparable pitch restoring moment and reserve Buoyancy. The impact of the different concepts, ESC 4100, the modified bow of the ESC (TUD 4100) and the ABC on the vertical accelerations in head waves can be seen in figure 8. Following the literature discussed above and the graphs depicted in figure 8, the proposed bow shape in order to minimise the vertical accelerations would be the AXE bow, however, in the next paragraph it is elaborated why this is not the case.



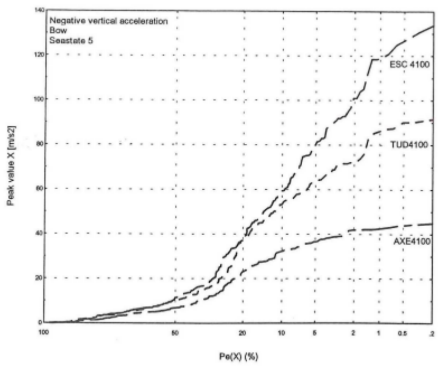


Figure 8: Distribution of peaks of negative vertical accelerations at the bow for the ESC4100, TUD4100 and the AXE4100

6.2 Considerations of the Bow Design

As discussed in the previous subsection, specific and well-considered bow designs are an effective way to minimise the vertical accelerations in head waves. However, designing a tender with this goal for a company with a complicated operation profile such as 'het Loodswezen' is not as straightforward as it seems and therefore different limitations exist and considerations and solutions should be made and found.

Just like any new development in engineering, each bow design and concept has its pros and cons. The literature discussed earlier will result in AXE bow for the new tender design with the main advantage that the vertical accelerations will be much lower than the conventional bow shape of the pilot tenders of 'het Loodswezen'. Another important advantage is that the resistance will also be lower than for conventional hulls, due to the longer waterline and slender lines plan. [15]

According to the MO's, there are some disadvantages of such a bow shape which outweighed the advantages and led to the choice for a conventional bow shape when designing the M-class tenders. It is important to note that these disadvantages are solely based on the experiences of the crew and pilots of 'het Loodswezen' and are not scientifically proven. A first disadvantage as well as the most important one is that the AXE bow compromises the mode of operation as explained in chapter 3. The MO's claimed that the AXE bow has the tendency to sail parallel alongside a cargo ship, once the controlled collision has took place and according to 'het Loodswezen' the safety of their pilots is being compromised.

A second significant drawback is the potential difficulty in sailing away from the cargo ship after the pilot transfer due to the reduced manoeuvrability caused by the deepened forefoot. After a more in-depth discussion with other MO's and from Damen, it became apparent that the concern was not fully grounded in marine engineering principles. Discussions with Damen revealed that piloting companies in other countries do not face major issues with reduced manoeuvrability of AXE bow-like shaped tenders. Damen acknowledged that the manoeuvrability might be slightly lower, but emphasised that the jets on the tenders of 'het Loodswezen' could adequately compensate for this, ensuring that disengaging from the cargo ship is manageable. It also became clear that the claim was more about the tendency of the AXE bow to sail parallel alongside a cargo vessel rather than disengaging from it, which led to claims of poor manoeuvrability. This highlights the importance of critically evaluating every opinion, proposition or claim, demonstrating that these claims warrant consideration but are not scientifically substantiated.

Experience of MO's, experts and literature combined lead to a AXE bow-like shaped hull form of which the tendency to sail parallel alongside a cargo vessel is limited, in order to prevent compromising the mode of operation of 'het Loodswezen'. Different aspects could help to achieve this goal and are summarised with the following three questions:

- Which mechanisms/concepts could be applied in order to reduce the drawbacks of an axe-bow like hull shape?
- Could the deck be designed in such a way that the same mode of operation could still be used, while the flare in the bow is heavily reduced compared to the conventional bow shape?
- To what extend can the bow be modified to reduce peak vertical accelerations, without compromising the mode of operation?

After answering these three questions, a final bow design, including deck configuration and potential mechanisms to improve manoeuvrability can be selected in order to reduce the vertical accelerations compared to the currently serving pilot tenders. These three aspects will be discussed in the following three subsections.

6.3 Iteration towards final bow and hull shape

This section focuses on the development of the final bow and hull shape through an iterative process. Multiple design iterations will be created and analysed to evaluate their impact on the vertical accelerations in waves. The results from each iteration will inform adjustments, aimed at further minimising the vertical accelerations.

6.3.1 Series 65

The initial basis for the new hull design is a standard planing hull form. For this purpose, the Series 65, depicted in Figure 9, was selected. However, the new tender design is subject to constraints established in chapter 4, including the beam dimensions determined in chapter 5. Consequently, the Series 65 was scaled to meet these specified dimensions, as detailed in table 3. While the Series 65 is a well-documented planing hull form, the vertical accelerations in head seas under these specific constraints remain uncertain, necessitating further analysis in Fastship.

Before proceeding with this analysis, a preliminary stability assessment is required to verify whether the initial stability of the scaled design meets the stability criteria. This evaluation will be based on the GM, calculated using the following formulas:

$$BM = I_{xx}/Displacement \tag{2}$$

$$KM = KB + BM \tag{3}$$

$$GM = KM - KG \tag{4}$$

The waterplane area, KB, LCB and moment of inertia will be derived using Rhinoceros 7 software, while the KG value is based on the Mira, set as boundary condition in chapter 4. Table 4 presents these calculated values for the scaled Series 65.

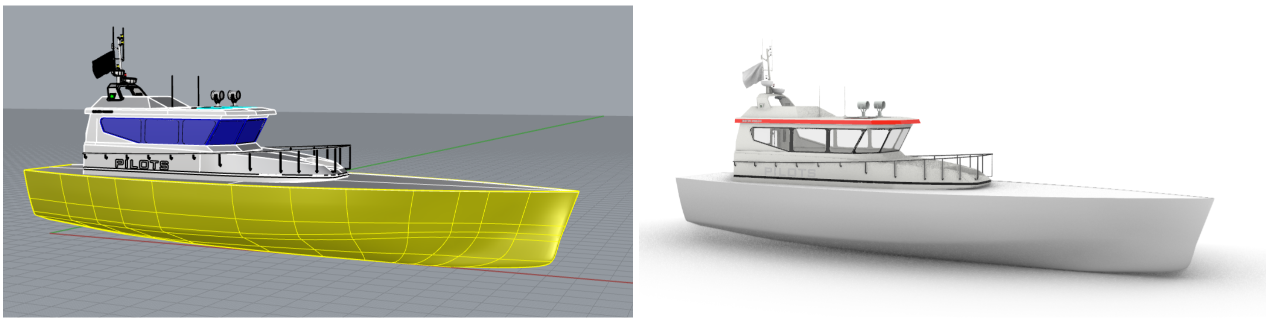
In consultation with Jaap Gelling and based on the SPi 2205, a minimum GM value of 1.5 metres was identified as necessary for a pilot tender. However, as shown in table 4, the adjusted Series 65 does not meet this requirement. So, the hull design must be modified in the first iteration to increase the GM. Given that the KG is constrained at 2.1 metres, this adjustment will involve modifying other aspects of the hull design, potentially leading to increased vertical accelerations.

Table 3: Main dimensions Series 65

Lwl (m)	Boa (m)	Tdesign (m)	D (m)	Displacement (tons)
21.41	6.46	1.18	2.9	45

Table 4: Stability data Series 65

Displacement (tons)	A_wl (m^2)	I_{xx} (m^4)	KB (m)	KG (m)	LCG (m)	LCB (m)	BM (m)	KM (m)	GM (m)
45	75.55	123.1	0.77	2.1	9.23	9.23	2.74	3.51	1.41



(a) Design of Series 65 Rhinoceros

(b) Render of the series 65

Figure 9: Designed Series 65

Following the simulation in Fastship, the probability of exceedance graph was generated and is presented in figure 10. The peak vertical acceleration for the initial design is approximately $73m/s^2$. This serves as the baseline for the iterative design process, with the ultimate goal of achieving a final hull design that shows significantly lower peak vertical accelerations. However, as previously noted, the primary objective of the first iteration is to ensure an adequate initial stability. This adjustment may result in an increase in vertical accelerations, which will be addressed in subsequent iterations.

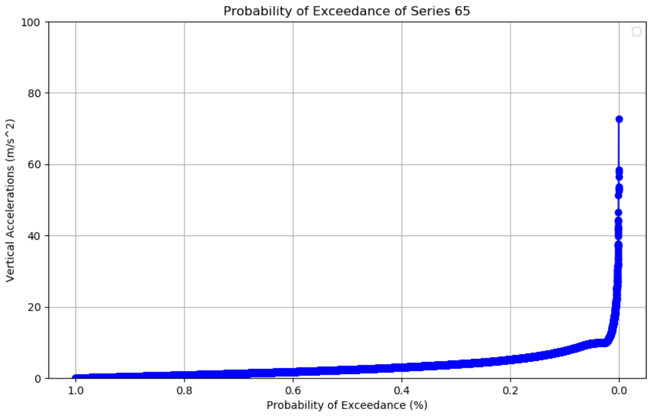


Figure 10: Probability of exceedance of the vertical accelerations of the Series 65 (B = 6.46 m)

6.3.2 Stan Pilot 2205

As previously mentioned, the Series 65 hull serves as the starting point for the iterative design process. Although the proposed bow shape is the AXE bow, it was determined that this configuration is not suitable for a pilot tender operated by 'het Loodswezen'. Literature highlights that the AXE bow represents an extreme design that significantly reduces vertical accelerations [6]. Extensive research spanning many years and substantial resources have been devoted to developing this bow shape to minimise vertical accelerations of high speed vessels in head seas. Given the substantial investment and specialised nature of the AXE bow, the Stan Pilot 2205, which is equipped with the AXE bow, can be considered a practical performance benchmark for the iterative process. Consequently, it is anticipated that the peak vertical accelerations of the final tender design will not be lower than those of the SPi 2205.

While analysing figures 6 and 10, the initial assumption appears incorrect, as the peak vertical accelerations for the 6.46 metre wide tender are approximately the same. However, two factors explain this outcome: the CoG in x-direction and the use of the Planing Hull Form.

The Stan Pilot 2205 is an existing vessel, and its ship data, including the CoG(x), was obtained from Damen. In contrast, the CoG(x) for the Series 65 is not available and has been assumed to be equal to the CoB(x), as outlined in chapter 4. Since vertical accelerations of vessels in head seas are heavily influenced by the CoG(x), comparing the results without considering this difference leads to unreliable conclusions.

Additionally, the results from Fastship are impacted by the sinkage and trim, both critical input parameters, as discussed in chapter 5.2.2. The sinkage and trim at a vessel speed of 18 knots were determined using Planing Hull Form, which is based on the DSDS database. However, as explained in chapter 5, the DSDS does not account for the AXE bow, which leads to slight deviations in the Fastship results. Consequently, a direct comparison between figures 6 and 10 is not valid, as the results for the SPi 2205 are influenced by several factors.

To provide a clearer indication of the design limits for this iteration, the simulation of the SPi 2205, with a beam of 6.46 metres, will be rerun. This time, the CoG(x) will be set equal to the CoB(x) and the sinkage and trim values will be derived from the calm water characteristics presented in the paper of Lex Keuning about the development of a new tender for the KNRM [3]. This paper provides calm water characteristics for the Arie Visser and two concepts for a new KNRM vessel, with one concept incorporating the AXE bow with dimensions nearly identical to the proposed new pilot tender. By using these more accurate sinkage and trim values, the results from the Fastship simulation will be more reliable, as shown in figure 11.

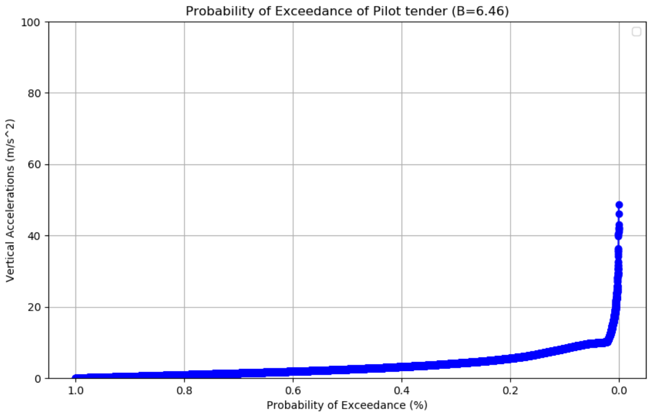


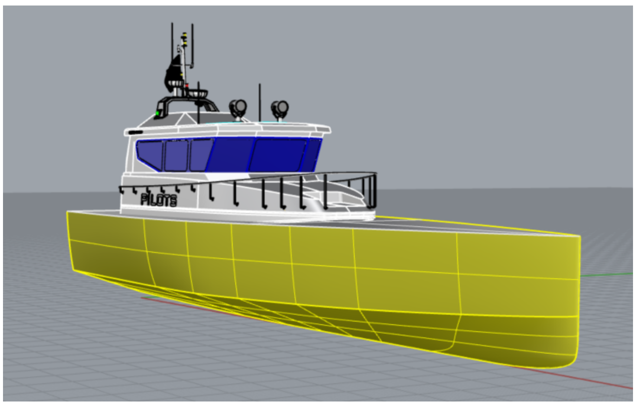
Figure 11: Probability of exceedance of the vertical accelerations of SPi 2205 (B=6.46m) with LCG = LCB

From these results, it can be concluded that the limit for the peak vertical accelerations of this iterative design process is 48.5 m/s^2.

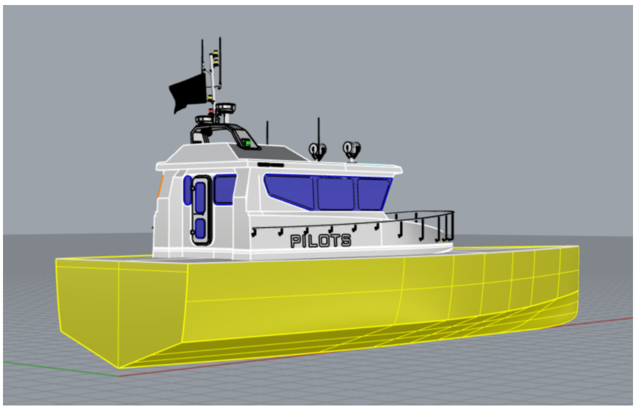
6.3.3 Iteration 1

The primary objective of the first iteration was to enhance the initial stability compared to the Series 65. To achieve this, the chine was maintained at consistent height along the entire hull length and the twist, representing the variation in deadrise along the hull, was minimised. Additionally, the afstship was widened to increase buoyancy.

However, the central focus of the thesis remains the reduction of vertical accelerations in head waves. Retrieving inspiration from the bow modifications of the ESC and AXE bow, the flare in the bow and the sides of the tender was reduced, as supported by literature of Lex Keuning [14] [6]. These modifications resulted in the hull design illustrated in figure 12 with the corresponding main dimensions listed in table 5.



(a) Design of Iteration 1: front view



(b) Design of Iteration 1:Back/side view

Figure 12: Iteration 1

Table 5: Main dimensions Iteration 1

Lwl (m)	Boa (m)	Tdesign (m)	D (m)	Displacement (tons)
22	6.46	1	2.9	45

Table 6 presents the stability characteristics of the first iteration. The data indicates that the stability is well above the required threshold, as evidenced by a GM of 2.87 metres. When these stability characteristics are linked to the results of the Fastship simulation, shown in figure 13, it becomes clear that the peak vertical accelerations have increased compared to the Series 65, reaching a maximum of 81 m/s^2.

However, the substantial GM value of 2.87 metres provides significant flexibility for further modifications without compromising the initial stability. Consequently, several key adjustments are planned for the next iterations. First, the deadrise will be increased to 25 degrees, following the findings of Van den Bosch [5], which suggest that a greater deadrise angle can significantly reduce peak vertical accelerations in head waves.

Second, the height of the chine will be varied along the vessel's length. This adjustment will narrow the foreship, aligning with the principles of the AXE bow, which emphasises reducing flare and creating a slender bow profile [6]. These modifications are expected to improve the seakeeping behaviour while maintaining adequate stability.

Table 6: Stability data Iteration 1

Displacement (tons)	$A_w l$ (m^2)	I_{xx} (m^4)	KB (m)	KG (m)	LCG (m)	LCB (m)	BM (m)	KM (m)	GM (m)
45	92.35	194.49	0.68	2.1	9.07	9.07	4.49	5.17	2.97

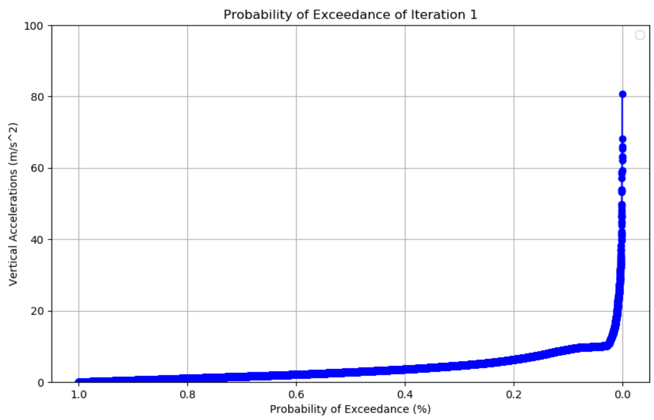


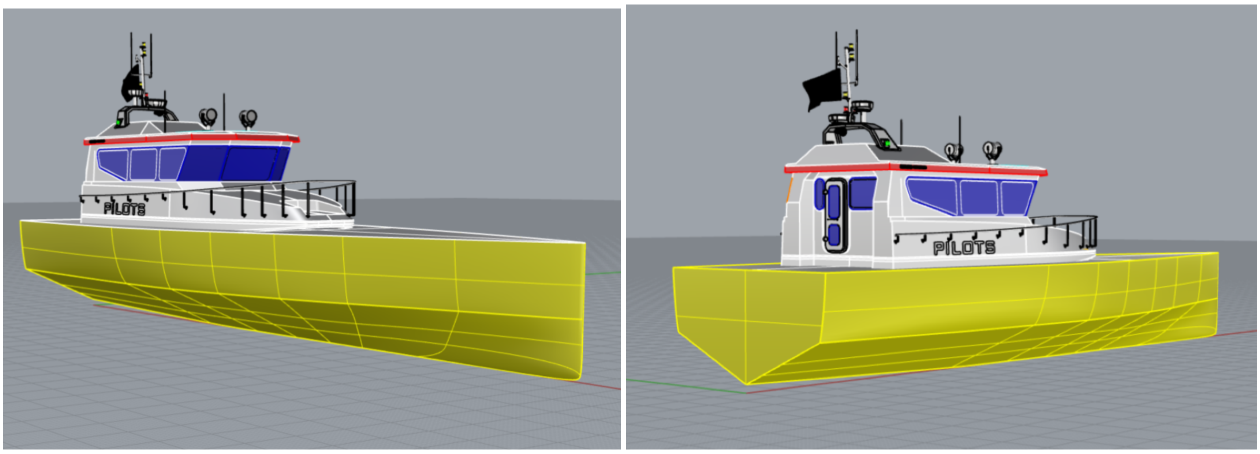
Figure 13: Probability of exceedance of the vertical accelerations of the Iteration 1

6.3.4 Iteration 2

As highlighted in the previous section, the substantial stability of Iteration 1 allowed for adjustments to enhance performance. One of these modifications was an increase in the deadrise angle to 25 degrees, aiming to reduce the vertical peak accelerations, as suggested by Van den Bosch [5]. This modification was implemented in Iteration 2, with its design illustrated in figure 14. The increase in the deadrise angle significantly impacted the GM value, shown in table 8, as well as draught, detailed in table 9. Furthermore, figures 13 and 15 demonstrate that increasing the deadrise angle from 18.5 to 25 degrees resulted in a 33.5% reduction in peak vertical accelerations, as the peak accelerations are decreased from 81 to 55.2 m/s^2.

Table 7: Main dimensions Iteration 2

Lwl (m)	Boa (m)	Tdesign (m)	D (m)	Displacement (tons)
21.95	6.46	1.17	2.9	45



(a) Design of Iteration 2: front view

(b) Design of Iteration 2: Back/side view

Figure 14: Iteration 2

Table 8: Stability data Iteration 2

Displacement (tons)	$A_w l$ (m^2)	I_{xx} (m^4)	KB (m)	KG (m)	LCG (m)	LCB (m)	BM (m)	KM (m)	GM (m)
45	81	127.08	0.80	2.1	9.158	9.158	2.82	3.62	1.52

An essential consideration in the development of the 'tender of the future', as outlined in the introduction, is the reduction of emissions. This objective can be approached through the adoption of green energy technologies, which are currently the focus of research within 'het Loodswezen'. Another effective strategy is minimising fuel consumption, which necessitates a critical desingn adjustment in the next iteration. Specifically, in this iteration, the chine is raised to 1.31 metres above the keel by increasing the deadrise angle.

The chine, however, plays a crucial role in reducing the resistance and, consequently, fuel consumption. A well-defined hard chine prevents water from rising up the hull sides, thereby minimising drag. Additionally, chines with a flat area underneath contribute to the pressure build-up, which enhances planing efficiency and further reduces resistance. For optimal performance, the chine must be positioned at an ideal height.

Currently, the chine placement does not meet these criteria, as the chine is raised to 1.31 metres. The optimal position, as recommanded by Jaap Gelling, is approximately 5 cm below the waterline in the aft section. Alternatively, the chine should be located at a depth of 1.5-4% of the chine's maximum beam below the waterline, equating to approximately 6 cm [16]. Adjusting the chine height to these specifications will be a key focus in the next design iteration, as discussed in the following section.

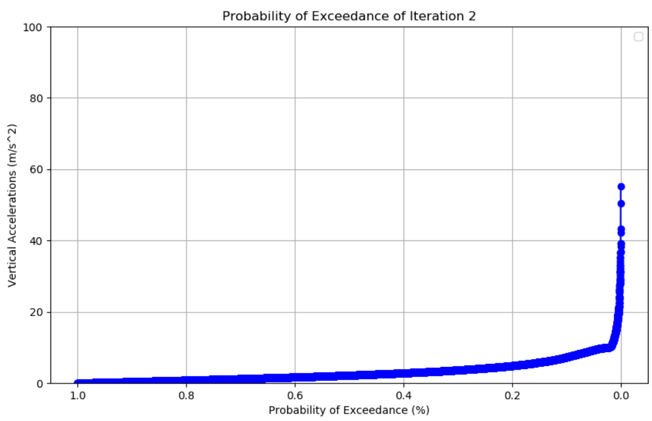


Figure 15: Probability of exceedance of the vertical accelerations of the Iteration 2

6.3.5 Iteration 3

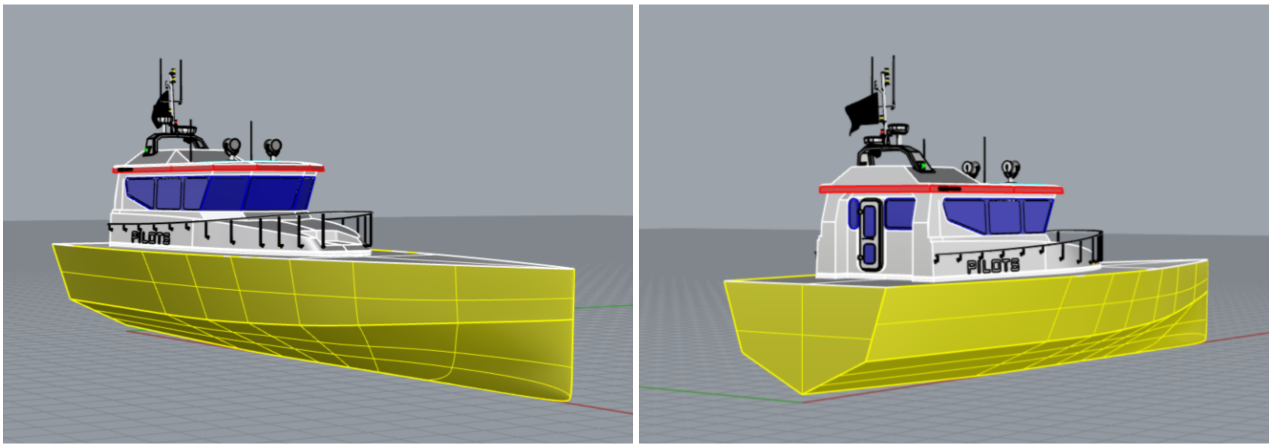
As discussed in the previous section, the chine height was varied until it reached the position of 6 cm below the waterline. This modification also caused a slight change in the draught, as shown in table 9. By optimising the chine height, the resistance is expected to decrease. However, with this modification, the deadrise angle and chine height remain constant over the entire hull length.

Upon reviewing various planing vessels and relevant literature, it becomes evident that the chine typically rises slightly up towards the bow [16]. Furthermore, a deeper exploration of the literature reveals that reducing the flare and narrowing the bow positively impact vertical accelerations [6]. This adjustment can be achieved by introducing a twist, thereby altering the deadrise angle near the bow.

Both these refinements have been incorporated into Iteration 3, as illustrated in figure 16. The variation in chine height along the hull length compared to iteration 2 is depicted in figure 17.

Table 9: Main dimensions Iteration 3

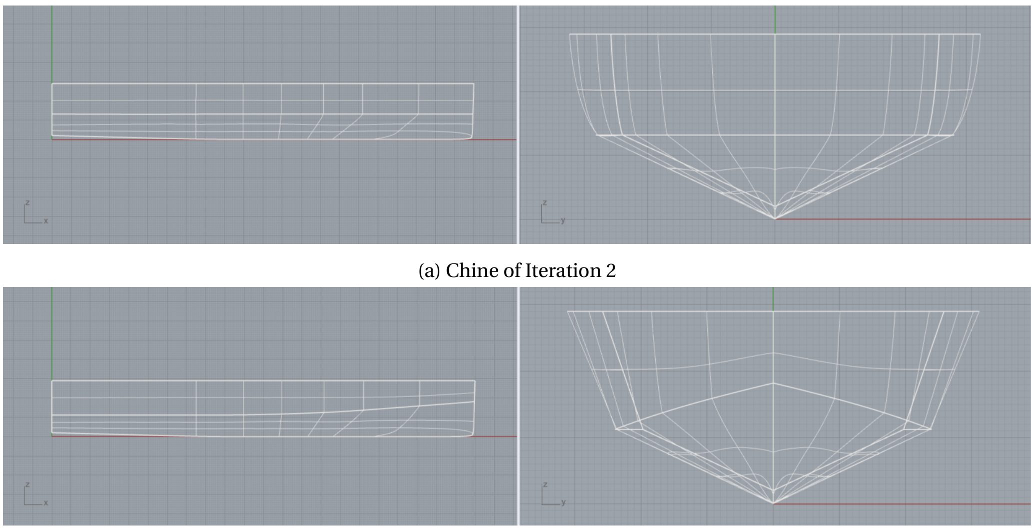
Lwl (m)	Boa (m)	Tdesign (m)	D (m)	Displacement (tons)
21.95	6.46	1.18	2.9	45



(a) Design of Iteration 3: front view

(b) Design of Iteration 3: Back/side view

Figure 16: Iteration 3



(a) Chine of Iteration 2

(b) Chine of Iteration 3

move

Figure 17: Chines of Iteration 2 and 3

In figure 18, the impact of the design adjustments on the peak vertical accelerations is shown and it can be noted that a reduction from 55.2 to 52.2 m/s^2 was established. In order to clarify the difference, a simulation was performed of Iteration 2.1. In Iteration 2.1, the chine was lowered to the height of 1.12 metres, as explained before, without conducting any further adjustments. The results of this simulation, depicted in Appendix C, show that lowering the chine impacts the vertical accelerations slightly. Because of this finding, it can be concluded that the reduction in vertical peak accelerations due to Iteration 3 is mainly the result of elevating the chine towards the bow and by this narrowing the bow.

A remarkable fact is that the peak vertical accelerations for Iteration 3 are comparable to those of the AXE bow, which serves as the lower benchmark, as shown in figure 11. Specifically, the peak vertical accelerations for Iteration 3 and the SPi 2205 are 52.2 m/s^2 and 48.5 m/s^2, respectively. It is important to note that Iteration 3 features a higher deadrise angle than the SPi 2205, which positively influences the results for iteration 3.

Upon closer examination of the design of Iteration 3, it becomes apparent that the bow is similar to the AXE bow design. While this contributes to reduced vertical accelerations, it raises concerns about potential compromises to the current mode of operation of 'het Loodswezen'. The research question addressed in this chapter: "To what extent can the bow and hull be modified without compromising the current mode of operation?", remains particularly relevant. Given the similarity to an AXE bow design, operational performance could be affected. Furthermore, as indicated in table 10, the initial stability does not meet the boundary condition of a GM value of 1.5 metres. To address these issues, the deck at the bow should be modified to retain a wider, rounder circumference that supports the existing mode of operation. Additionally, modifying the waterplane area is essential to improve stability. These aspects will be critical focus points in the next iteration.

Beyond bow modifications, the aft ship also requires attention. While the hard chine in Iteration 3 was intended to reduce drag and thereby fuel consumption, closer inspection reveals a transition to a blunt chine. This change negatively affects planing performance and efficiency, so the aft section must also be refined in the next iteration.

Table 10: Stability data Iteration 3

Displacement (tons)	A_wl (m^2)	I_{xx} (m^4)	KB (m)	KG (m)	LCG (m)	LCB (m)	BM (m)	KM (m)	GM (m)
45	79.38	122.41	0.802	2.1	9.044	9.044	2.72	3.52	1.42

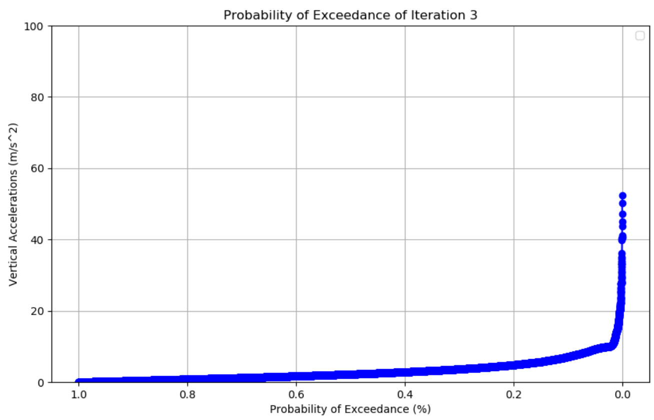


Figure 18: Probability of exceedance of the vertical accelerations of the Iteration 3

6.3.6 Iteration 4

As already mentioned, the tender under development features a hard chine planing hull, a design choice that offers distinct advantages. Before diving into one such advantage, it is useful to understand the working principle of a planing hull. The transition from displacement mode to planing mode is governed by Newton's third law of motion. As the hull moves forward, it exerts a force on the water and vice versa, the water exerts a reacting force on the hull. This force per unit area is known as the hydrodynamic pressure.

The region of maximum pressure is called the stagnation point or line, which can be seen in figure 19. For vessels with a deadrise, like the current design, this stagnation line sweeps back and intersects with the hard chine, where the water flow separates from the hull. This separation prevents water from climbing up the hull, thereby avoiding additional drag [17]. However, concerns have been raised about the blunt chine at the aft section of the vessel. A poorly defined separation at this location can fail to effectively shed water, leading to increased drag.

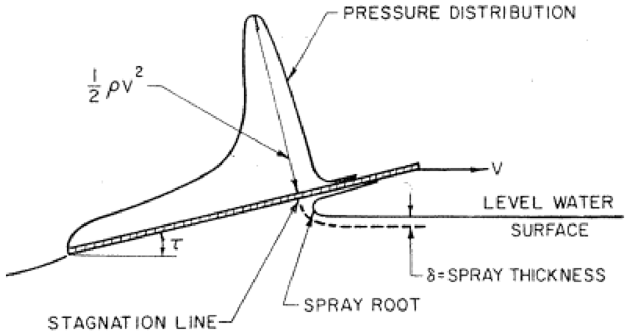
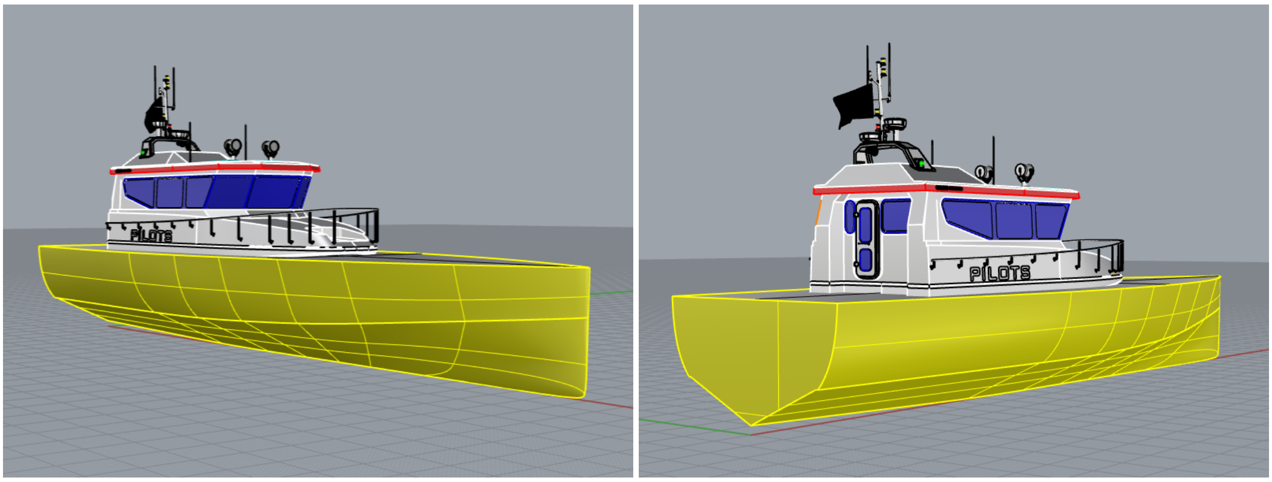


Figure 19: Pressure distribution on a flat plate

To address this issue, one approach is to redesign the aft section to create a more effective hard chine. A simpler and more practical alternative, however, is to add spray rails. Spray rails ensure that water is properly separated from the hull, reducing resistance. Incorporating spray rails on a planing hull can reduce drag by up to 10% [18]. This is a significant benefit, especially considering that 'het Loodswezen' aims to reduce fuel consumption, as noted in the introduction. Thus, while addressing slamming issues remains priority, the vessel's resistance must also be minimised to meet efficiency goals and therefore the spray rail is incorporated in iteration 4.

While seeking for the ideal design for 'het Loodswezen' to reduce the vertical accelerations, it is crucial to account not only for resistance but also for the operational requirements of 'het Loodswezen'. One key consideration is the mode of operation, which requires a sufficiently wide deck at the bow to allow sailing at an angle during transfer operations. To accommodate this, the deck width at the bow was increased compared to iteration 3, enabling the vessel to operate in a manner consistent with current practices and enhancing operational efficiency.

With these adjustments, namely the widened bow deck and the addition of spray rails, as shown in figure 20, the main dimensions of the vessel remain the same as those in iteration 3 (table 11). However, the addition of spray rails has altered the waterplane area, increasing its moment of inertia and thereby improving the vessel's initial stability, as detailed in table 12. This addresses a key requirement since iteration 3 failed to meet initial stability criteria.



(a) Design of Iteration 4: front view

(b) Design of Iteration 4: Back/side view

Figure 20: Iteration 4

Table 11: Main dimensions Iteration 4

Lwl (m)	Boa (m)	Tdesign (m)	D (m)	Displacement (tons)
21.95	6.46	1.18	2.9	45

Table 12: Stability data Iteration 4

Displacement (tons)	$A_w l$ (m^2)	I_{xx} (m^4)	KB (m)	KG (m)	LCG (m)	LCB (m)	BM (m)	KM (m)	GM (m)
45	80.53	128.72	0.803	2.1	9.04	9.04	2.86	3.66	1.56

Simulations performed in Fasthip reveal a slight increase in maximum vertical accelerations for iteration 4 compared to iteration 3, at 54.3 m/s^2 versus 52.2 m/s^2, as shown in figure 21. This minor difference can be attributed to two factors.

First, while the widened bow deck might be expected to influence vertical accelerations, the effect is minimal. This is because the underwater hull geometry of both iterations is nearly identical at the bow, and the deck's changes are relatively small. Furthermore, the impact of the slightly widened deck on the vertical accelerations is low as the depth of the vessel is 2.9 metres and the simulations are performed in a significant wave height of 2.25 metres.

Second, the addition of spray rails slightly increases the vessel's waterplane area width in the aftship, as indicated by comparing the waterplane areas in tables 16 and 20. However, this change has a small effect on vertical accelerations, given the small magnitude of the width increase and its aftship location. Furthermore, the bow's narrow profile with minimal flare significantly reduces vertical accelerations by minimising non-linear Froude-Krylov forces and hydrodynamic lift forces [6] [13]. Therefore, the vertical accelerations are already relatively low.

Iteration 4 represents a promising concept, achieving relatively low vertical accelerations while incorporating modifications to enhance resistance and operational efficiency without significantly compromising performance. Nevertheless, there is still room for improvement in future iterations.

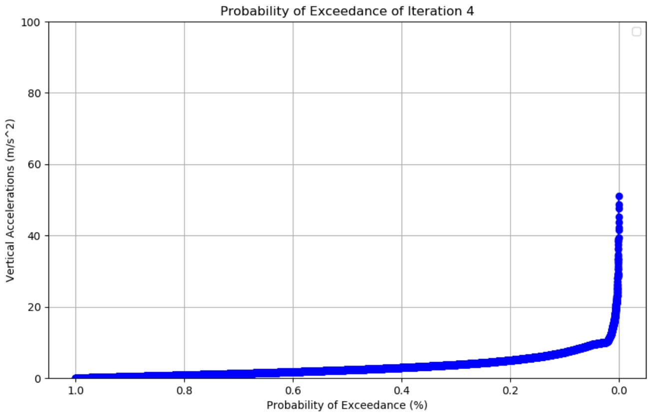


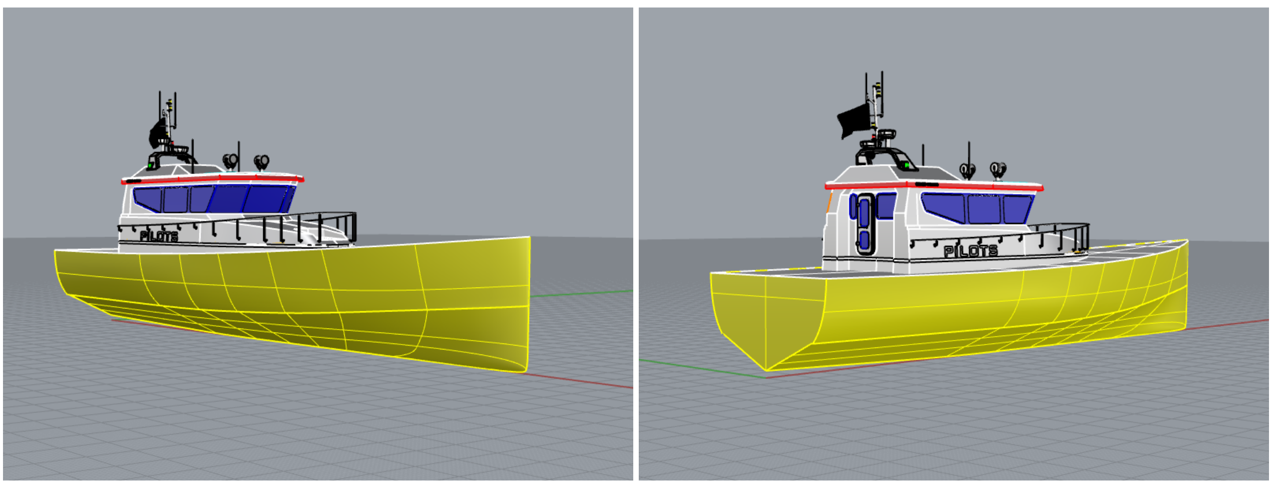
Figure 21: Probability of exceedance of the vertical accelerations of the Iteration 4

6.3.7 Iteration 5

In the earlier iterations, several modifications were made to narrow the underwater hull and improve resistance. These included lowering the chine, raising th chine towards the bow, increasing deadrise angle and adding spray rails. However, these adjustments, particularly those aimed at narrowing the bow, introduce potential risks that require consideration.

One potential potential concern is an increased sensitivity to broaching. However, research indicates that this risk is negligible. During the development of a new KNRM concept, Marin conducted tests to evaluate broaching tendencies. These tests, involving a design with dimensions comparable to the pilot tender and featuring an adapted AXE-bow, revealed no significant instances of broaching [3]. Similarly, a comparative study by [19] examined the Wave-Piercer, Enlarged ship concept and AXE bow designs, with no notable broaching tendencies observed for the ESC and AXE bow. However, in both studies, fixed fins were incorporated in the model in order to prevent broaching. However, the tendency towards broaching was also investigated without these skegs [13]. This study concluded that the yaw and roll do indeed increase, but that there was no increase in tendency for broaching. As such, further investigation into broaching was deemed unnecessary.

A more pressing concern is the risk of bow diving, which could lead to greenwater ingress and a loss of buoyancy. This issue has been addressed by slightly raising the deck height towards the bow, as illustrated in figure 22. The elevation follows the example of the Stan Pilot 2205 by Damen, raising the bow deck from 2.9 metres to 3.65 metres, with the deck amidships increased to 3.02 metres, as noted in table 13. This adjustment ensures sufficient reserve buoyancy to mitigate bow diving.



(a) Design of Iteration 5: front view (b) Design of Iteration 5: Back/side view

Figure 22: Iteration 5

Table 13: Main dimensions Iteration 5

Lwl (m)	Boa (m)	Tdesign (m)	$D_midships(m)$	Displacement (tons)
21.95	6.46	1.18	3.02	45

The elevated deck also provided an opportunity to further widen the bow deck without altering the bow shape significantly below 2.9 metres. This enhancement improves operational efficiency by creating a broader, rounder deck while maintaining the current mode of operation. The impact on vertical accelerations in waves remains minimal, with peak vertical accelerations rising slightly from 54.3 to 56.2 m/s^2, as shown in figure 23.

With this iteration, the design concept appears near-final. However, further refinement of the deck design could enhance operability. This will be explored in the next chapter. Additionally, concerns about the tender's manoeuvrability during transfer operations have been raised. Specifically, within 'het Loodswezen', it is believed that a sharp bow could complicate movement away from the cargo ship. While Damen claims that the tender's jets provide sufficient thrust to counteract this issue, a brief investigation into potential solutions will be conducted in the following section.

Table 14: Stability data Iteration 5

Displacement (tons)	A_wl (m^2)	I_{xx} (m^4)	KB (m)	KG (m)	LCG (m)	LCB (m)	BM (m)	KM (m)	GM (m)
45	80.51	128.88	0.803	2.1	9.04	9.04	2.86	3.67	1.57

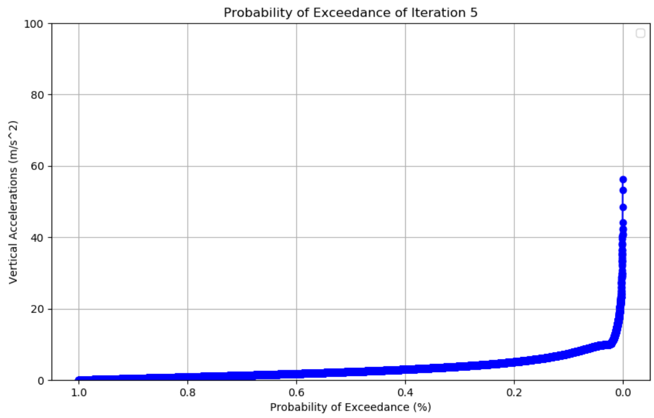


Figure 23: Probability of exceedance of the vertical accelerations of the Iteration 5

6.4 Potential Mechanisms and Concepts to Improve Manoeuvrability

As previously mentioned, 'het Loodswezen' has emphasised several main drawbacks in their opinion of the AXE-bow and similar hull shapes. One way to mitigate these drawbacks is to install mechanisms which will enhance the vessel's manoeuvrability, thereby increasing the possibility to sail under an angle alongside a cargo ship. However, such mechanisms will be expensive and sophisticated. For instance, a simple bow thruster would be ineffective, as both the tender and cargo ship are sailing at a forward speed of 8 knots in order to keep the manoeuvrability high. This section will explore potential mechanisms to improve the manoeuvrability.

A feasible option to increase the manoeuvrability of a pilot tender is the rotor manoeuvring system (RMS) of Damen, depicted in figure 24. This system is a retractable Magnus bow rotor which increases manoeuvrability by utilising the Magnus effect. The rotor generates lift by rotating around its vertical axis and acts in free flow just as a wing. Originally, the idea was to incorporate these rotors in the AXE bow's shape. However, tests showed that the rotor was most effective when it extends below the lowest, most forward, part of the AXE bow. Because of this placement, the rotor becomes impressively effective. Due to the Axe bow's geometry, the rotor remains far beneath the free surface, also in waves, which prevents free surface effects such as loss of lift and ventilation. Also the relatively large distance to the Centre of Gravity of the ship implies that a considerable roll motion is generated, which helps in reducing the roll motion. Additionally, another significant advantage of the RMS is that it can be retracted when not in use, therefore neglecting the negative effect on the resistance of the vessel [20].

Figure 24: Rotor Manoeuvring System (RMS)

The main idea behind this bow rotor was to enhance course stability and reduce the possibility of broaching in stern quartering waves. Figures 25 and 26 show that the Magnus Rotor significantly reduces the roll and yaw motion of the ship such a conditions. However, when full scale tests were performed with the SPi 2205 by Damen, the same vessel as the base model used in this Master's Thesis, it was expected that it would yield to an extra advantage. Specifically, when a pilot boards or disembarks from a cargo ship, a speed of 8 knots is maintained, as explained before. At this speed, the bow rotor would benefit from the forward motion, making the 'crabbing' manoeuvre of the pilot tender highly controllable. This also improves control when sailing away from the cargo ship, typically a challenging manoeuvre. An advantage of the full scale tests for this Master's Thesis is that the bow rotor was already tested on a 22 metres pilot tender and that the results match the results presented in figures 25 and 26. Therefore, it can be concluded that the sway and roll motions are reduced by up to 50 percent with the bow rotor and that the crabbing motion is indeed more controllable, even at higher forward speeds ([20]).

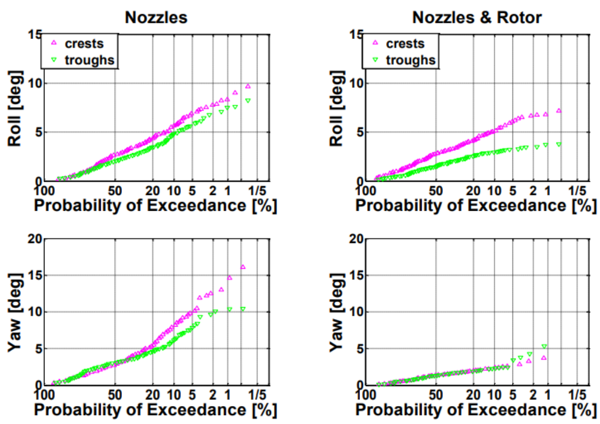


Figure 25: Probability of exceedance of a model with and without bow rotor during free sailing tests

For the continuation of this study, the bow rotor will be left out the design. The main reason is that the hull design itself will be developed in such a way that the current mode of operation will not be compromised. Next to this, it is up to 'het Loodswezen' if they want to invest in such a feature or not in case that they are unsatisfied with the manoeuvrability of the new tender design.

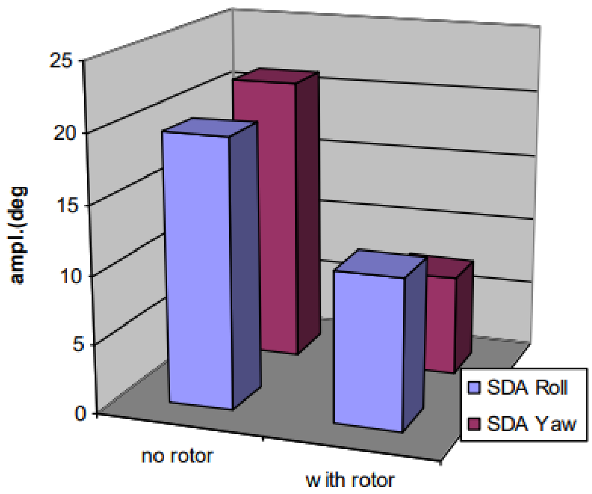


Figure 26: Single double amplitude of the roll and yaw motion with and without bow rotor in sea state with Hs=3.5 metres

6.5 Conclusion

In this chapter, the ideal bow and corresponding hull design were developed through an iterative process. Each iteration addressed specific challenges or sought to reduce vertical accelerations in head waves based on concepts from literature. This process culminated in the final Iteration 5, starting from a basic planing vessel, the Series 65. Key adjustments included the creation of a hard chine to enhance resistance, an increased deadrise angle and an elevated chine towards the bow to achieve a sharper profile. Additional modifications involved widening the bow deck and raising the deck height to provide reserve buoyancy and improve operational efficiency. These steps resulted in an optimised hull shape for 'het Loodswezen', balancing vertical acceleration mitigation with operational requirements and resistance optimisation.

To conclude, the resulting concept achieves peak vertical accelerations of 56.2 m/s^2, positioned within the benchmark range of 73 m/s^2 (series 65, upper bound) and 48.5 m/s^2 (SPi 2205, lower bound). Furthermore, 'het Loodswezen' retains the option to incorporate a bow rotor to enhance manoeuvrability during operations. These values of the peak vertical accelerations, combined with the adaptability of the design, highlight Iteration 5 as a promising solution. Moreover, further improvements are achievable through a refined deck design, presenting opportunities for even greater operational efficiency.

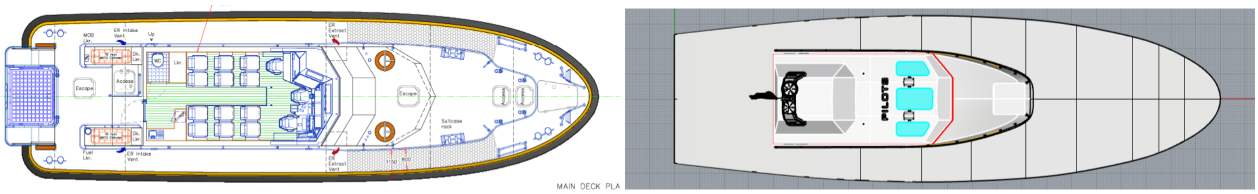
7 Deck design

The current pilot tenders of 'het Loodswezen' feature a wide, round deck, particularly at the front of the vessel. This design ensures the pilot transfer method used by 'het Loodswezen', where the vessel sails at an angle during the transfer process. However, this wide deck design has not been included in the new hull and bow design, as it was argued that minimising the flare in the bow is required in order to reduce the deck width. In this chapter, the ideal deck shape will be sought by answering the next question: 'Could the deck be shaped in such a way that the same mode of operation could still be used, while the flare in the bow is heavily reduced?'

7.1 Deck design 1

The first deck design is based on the principle of the current tenders: 'making the deck as wide and round as possible at the bow.' To achieve this, the deck shape was designed similarly to that of the existing tenders, as shown in figure 27. However, several key differences have been incorporated to enhance comfort onboard. Firstly, due to the increased buoyancy required in the bow and the resulting increased depth, the deck will be positioned higher compared to the current tenders. Another important feature is the flare in the bow, which has been minimised in the new hull design. However, to accommodate the deck design, a significant increase in flare is necessary. To mitigate the impact of this flare increase on vertical accelerations in head waves, the flare is positioned in the additional volume created by the deck height increase in the bow, as illustrated in figure 28. This positions the flare higher as in the Mira, although a flare increase still remains. As discussed in chapters 5 and 6, this increase could lead to higher vertical accelerations and potential slamming.

Simulations conducted in Fastship were used to compare design iteration 5 with deck design 1. As shown in Appendix A, the results reveal minimal differences between the two designs when tested in the wave conditions outlined in chapter 4. One possible explanation for this is that a significant wave height of 2.25 metres was used in the simulations, while both designs place the deck at a height of 3.65 metres at the bow (2.48 metres above the waterline). Furthermore, the designs are nearly identical underneath the depth height of 2.9 metres, resulting in almost the same body entering the water in waves and therefore the small variation. However, when both designs are tested in head waves with a significant wave height of 3 metres, a clear difference emerged, namely a peak vertical acceleration of 75.8 m/s^2 and 87.6 m/s^2 for iteration 5 and deck design 1 respectively. The wide deck design was shown to impact the vertical accelerations in a negative way when the tenders operate in the most challenging conditions they encounter, also shown in Appendix D.



(a) Deck design of the Mira

(b) Deck design 1

Figure 27: Comparison of deck design 1 and of the Mira

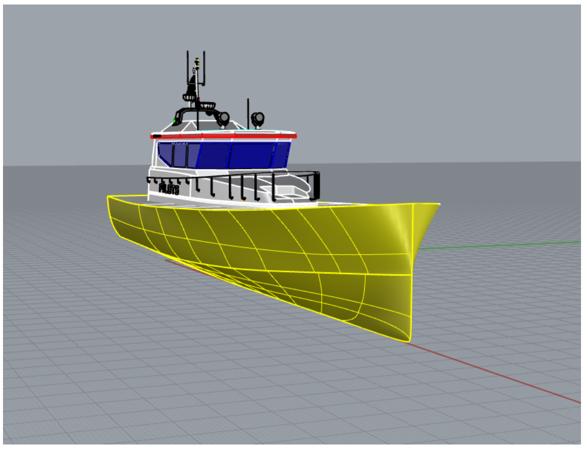


Figure 28: Deck design 1

Thus, deck design 1 maintains the current mode of operation, which was a key objective in the new design. However, it actually returns to the same deck design as the Mira, bringing with it the same issue of high vertical accelerations due to the increased flare. Consequently, further iteration of this deck design is necessary.

7.2 Deck design 2

This deck design represents a further iteration of deck design 1, with the aim of retaining the key advantage while addressing its main drawback, the increased flare. The primary goal was to maintain the rounded deck shape that allows the vessel to sail at an angle during pilot transfers while eliminating the negative affect of increased flare.

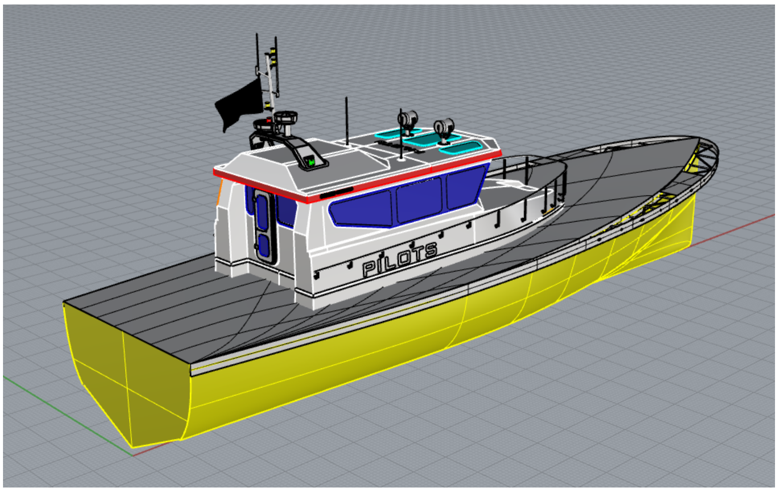
An initial concept was to recreate the shape of deck design 1 by incorporating holes in the deck. This approach would reduce the flare increase while preserving the overall deck shape. However, adding holes introduces local stress concentrations, requiring specialised structural analysis and reinforcement [21]. Based on this limitation, a new concept was developed that focuses on the circumference of the deck rather than its surface, as this makes the current mode of operation possible.

The new concept involves maintaining the hull and deck of iteration 5 while adding a structure with rods to recreate the same fender circumference as in deck design 1, as shown in figure 29. By doing so, the flare increase is avoided, resulting in lower vertical accelerations compared to deck design 1, while still enabling the same mode of operation.

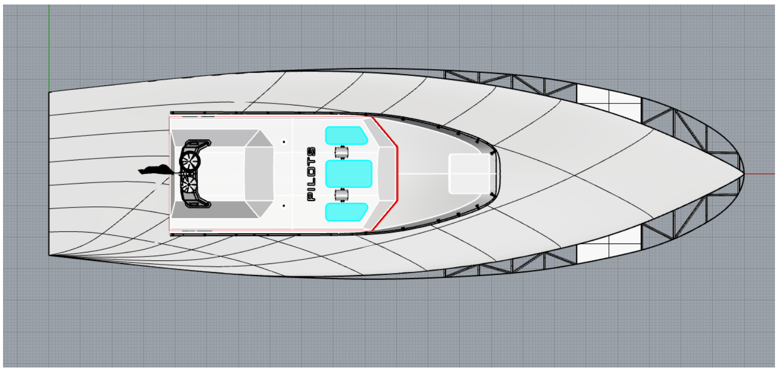
Despite resolving the flare issue, this design introduces several potential drawbacks. Firstly, the pilots are limited to a fixed area for transfers, reducing operational flexibility, particularly in severe conditions. Additionally, the combination of the sharp bow and the added structure may cause splashing water. While this is generally manageable, it could complicate operations if water heavily splashes onto the pilot or assisting crew during transfer.

Another concern is the empty space between the fendering and the hull. This gap poses safety risks, such as increased chances of missteps by pilots or crew. Moreover, it distances the crew from docking lines, complicating mooring operations. Finally, the structural and operational impacts of this added structure are uncertain. It is unclear how the hull will respond to the new loads or how the structure itself will perform over time, requiring further structural evaluation.

Given these challenges and potential drawbacks, another iteration will be developed to address these issues while retaining the key benefits of this design.



(a) Deck design 2: side view



(b) Deck design 2: top view

Figure 29: Deck design 2

7.3 Deck design 3

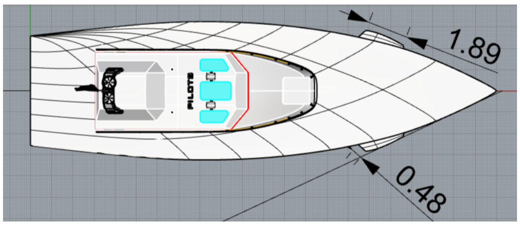
From the analysis of deck design 2, it became evident that maintaining the current operational method, sailing at an angle during transfer operations, relies primarily on the circumference of the deck or hull at the bow, rather than on the deck area itself. This was demonstrated in through the use of a rod-based structure in deck design 2. However, while this approach addressed some issues, it also introduced several drawbacks. Building on the same concept of using a structure rather than a full deck, and following consultations with Damen, a new design concept was developed: incorporating small overhangs mounted on the sides of the deck and hull. These overhangs enable angled sailing during transfer operations, as illustrated in figure 30.

The design, however, introduces a limitation. The angle at which the tenders can operate is predefined by the position and shape of the overhangs as shown in figure 30. This range is strictly limited, meaning the optimal operational angle must be carefully determined. A study or observational analysis is required to identify the most frequently used angles during tender operations before finalising the design.

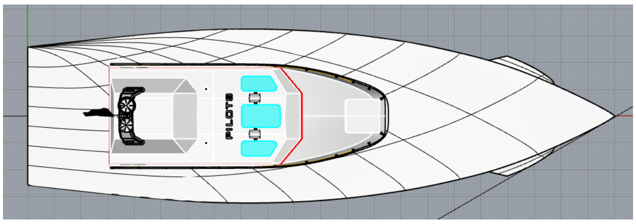
Despite this limitation, deck design 3 appears to be the most promising solution. The reasons are as follows:

- Eliminated flare increase: By adding only small overhangs instead of a full, round and wide deck, the problematic increase in flare, and its associated higher vertical accelerations, is avoided.
- Improved structural certainty: The potential uncertainties surrounding the structural behaviour of a rod-based framework are resolved with a simpler overhang design.
- Enhanced safety: The absence of holes in the deck or near the pilot transfer point reduces the risks of missteps and minimises the chance of water splashing onto the crew or pilots during operations.
- Retained operational flexibility: Unlike deck design 2, which required specified pilot transfer locations, this design avoids restricting operational flexibility.

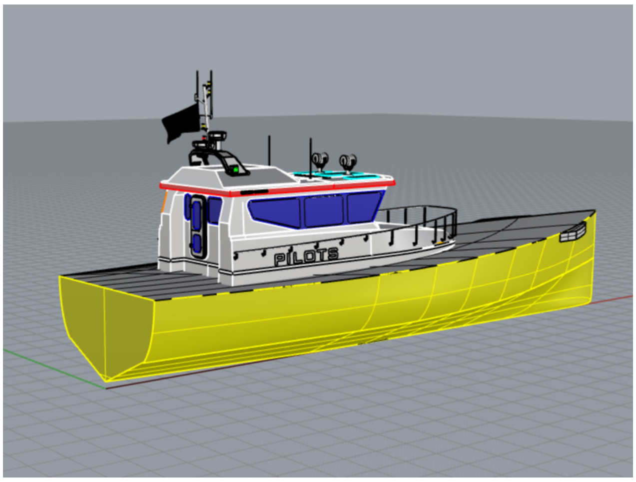
While the primary drawback remains the limited range of operational angles, further research can mitigate this issue by identifying and optimising the most suitable angle for operations. Taking all these factors into account, deck design 3 represents the most practical and promising solution. It will therefore be selected for further development.



(a) Top view: Sailing at angle of 25 degrees



(b) Top view: Sailing at 30 degrees



(c) Side view: Sailing at 30 degrees

Figure 30: Deck design 3

8 Sensitivity Study

All the results discussed in this research are based on simulations conducted using Fastship. However, it is still unclear to what extend these results are affected by certain input parameters. In this chapter, the reliability of the results will be examined and recommendations on how to interpret the results will be formulated.

8.1 Influence of input parameters

In chapter 5.2.2, the significance of various parameters was emphasised, particularly the influence of sinkage and trim. These parameters play a critical role in shaping the outcomes as they directly affect the a_{bf} and C_m values, which must be selected with care [9]. However, the prediction tool Planing Hull Form was utilised to determine sinkage and trim. This tool relies on a database of standardised planing hull forms, which introduces some deviations in the calculated sinkage and trim and by this influence the results.

Furthermore, a simplified version of Fastship was used, where each cross-section is defined by only five points: the keel, the height and width of the chine and the height and width of the deck. To enable rapid iterations and quick results, the number of cross-sections was also intentionally restricted. These constraints mean that not all curves and bends of the hull are accurately captured in Fastship. While these limitations facilitate quick simulations for early-stage concept analysis, they directly affect the accuracy of the results, which should therefore be interpreted with caution.

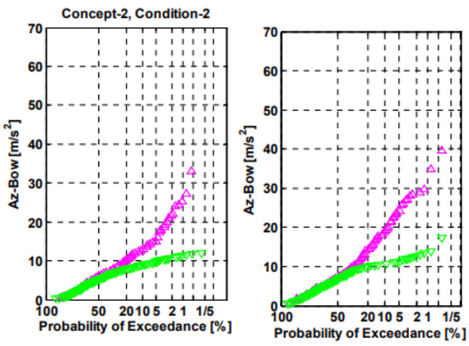
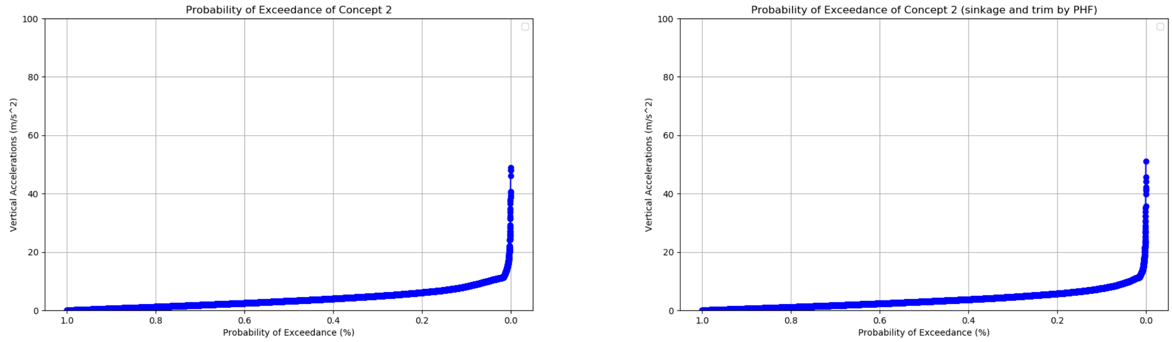


Figure 31: Probability of exceedance of Concept 2 depicted in [3]

To assess the impact of these limitations on the results, an additional simulation using Fastship will be conducted. In a study by Lex Keuning [3], two potential concepts for the new KNRM tender were evaluated and simulated in Fastship (see Figure 31) to determine the resistance and vertical accelerations. Concept 2, as described in that research, features an AXE bow and dimensions, excluding weight, almost equal to the final design in this Master's Thesis. Simulating this tender under the same conditions as the final design and comparing the outcomes provides a measure of the reliability of the results in this thesis.

To analyse the effects of a less detailed hull description, the use of a basic version of Fastship and the calculation of sinkage and trim using PHF, two simulations were performed. The first simulation used the sinkage and trim data described in the paper about the development of a new tender for the KNRM [3], while the second used the sinkage and trim calculated with PHF. The outcomes of these simulations are presented in figure 32.



(a) With sinkage and trim as described in [3]

(b) With sinkage and trim determined by PHF

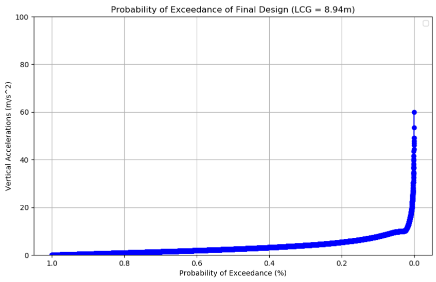
Figure 32: Probabilities of exceedance of Concept 2: simulated with Fastship

The results indicate that the limitations of the basic version of Fastship, particularly its restricted input variables and simplified representation of cross-sections, significantly influence the outcomes, with a variation of approximately 20% (40 m/s^2 vs. 49.7 m/s^2). This is evident from the weight calculation by Fastship, which deviates 8.5% compared to the value reported in the study of Lex Keuning [3] and verified in Rhino. Conversely, the impact of calculating sinkage and trim using PHF is minimal, as depicted in figure 32. Thus, the observed differences are largely from the constrained input parameters.

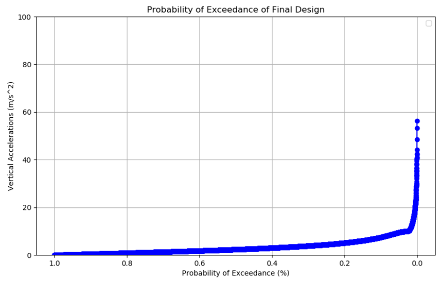
It is worth noting that, for every iteration, the weight calculations from Rhino and Fastship were cross-checked, with differences never exceeding 5 percent. This approach minimised deviations in the results. However, due to the inherent limitations in input variables, the results in this Master's Thesis should still be interpreted with caution.

Nevertheless, as long as the sinkage and trim values are calculated consistently across all designs using the same method, and deviations due to limited input parameters remain consistent, the results are valid for comparative purposes. Since each iteration represents only small adjustments from the previous concept, it is reasonable to assume similar deviations. In other words, while absolute accuracy may be affected, the relative differences between iterations can still indicate whether the adjustments made have successfully reduced vertical accelerations. Therefore, it can still be concluded which effect each iteration has on the vertical accelerations and therefore, which design choices will lead to the ideal tender for 'het Loodswezen'.

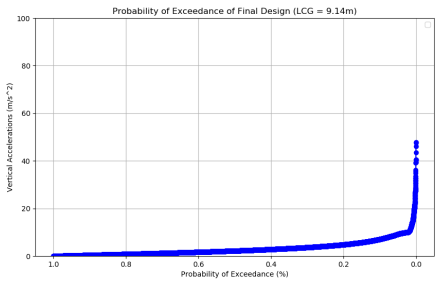
8.2 Influence of LCG



(a) LCG = 8.94 metres



(b) LCG = 9.04 metres



(c) LCG = 9.14 metres

Figure 33: Influence of LCG on the vertical accelerations

A crucial consideration in the design is the position of the LCG. The LCG significantly influences vertical accelerations, meaning any shift in its position could substantially affect results. In this conceptual design, the LCG was determined based on the LCB, as outlined in chapter 4. However, during the development of the complete tender design, the LCG is likely to shift. As illustrated in figure 33, such shifts can have both positive and negative effects on peak vertical accelerations. Therefore, careful attention is required during the final design stages to ensure the LCG is positioned advantageously or remains stable to minimise potential adverse impacts.

8.3 Conclusion

From these considerations, it can be concluded that the relative differences between the iterations are reliable. Therefore, conclusions can and will be drawn concerning the optimal hull design for a future tender of 'het Loodswezen'. However, caution is required when using the results directly in a new tender design, as the absolute values of the results are off by approximately 20% and heavily influenced by the LCG of a final tender design. Meaning that if the absolute values of the future final tender are required, an additional study into the seakeeping behaviour is advised.

9 Conclusion and Further Research

In this chapter, a brief conclusion will be formulated in which it will be argued whether or not the goal of the Master Thesis was met. Following on this conclusion, recommendations towards further research will be made. These recommendations will address the actions which are still required in order to implement this concept design into a future tender of 'het Loodswezen'.

9.1 Conclusion

9.1.1 Results

The new hull design for the 'Tender of the Future' project of 'het Loodswezen' was developed as part of this Research Project. The 'Tender of the Future' was initiated with the goal of renewing the fleet to achieve a significant reduction in emissions. The first step in this transition was the introduction of the M-class tender, which achieved a weight reduction of approximately 15 tonnes. Thereby, lowering fuel consumption and emissions. However, this reduction in weight also resulted in severe slamming. Within the 'Tender of the Future' project, which aims to develop a tender powered by alternative fuel, 'het Loodswezen' also identified the opportunity to redesign the hull to improve the seakeeping behaviour of their tenders. This objective formed the main goal of this Master's Thesis: "Delivering a new hull design for the tenders of 'het Loodswezen' which will reduce the vertical accelerations caused by waves compared to the currently used L- and M-class tenders."

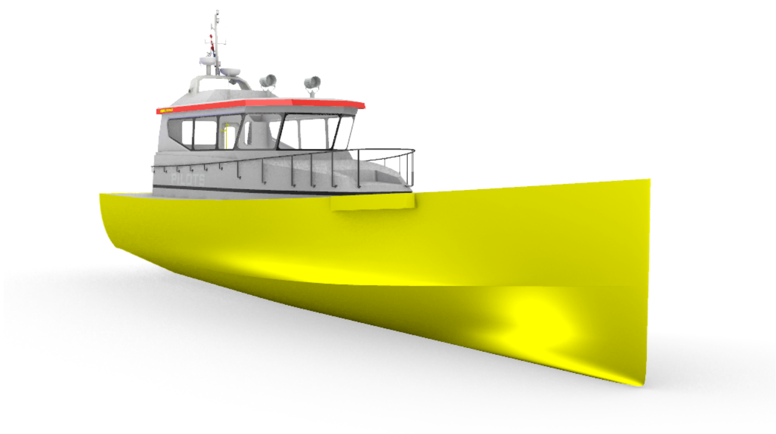
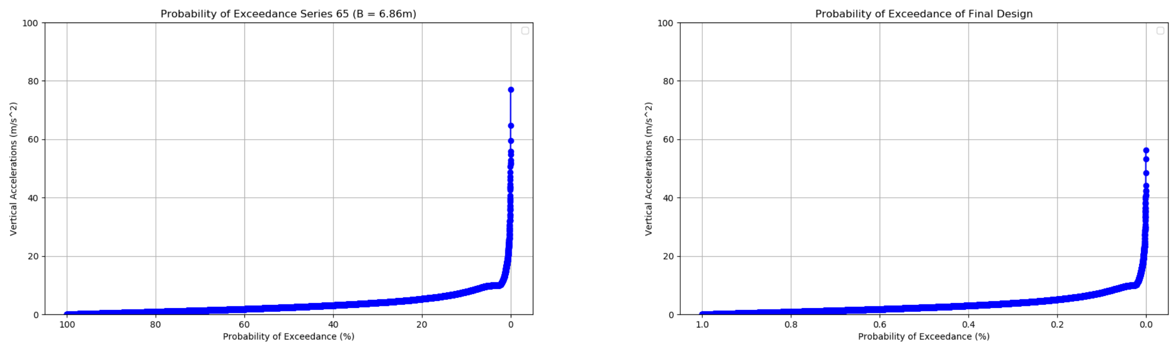


Figure 34: Final design

The resulting hull design, presented in figure 34, with main dimensions presented in table 15, is accompanied by its lines plan and different views in appendix E. To evaluate onboard comfort, the probability of exceedance of vertical accelerations was employed, as explained by Keuning [11]. This approach focuses on peak vertical accelerations, which significantly impact onboard comfort since the crew tends to react to the highest impacts experienced rather than average conditions. Figure **??** illustrates the probability of exceedance for the final design, providing insight into its performances. Thus, the outcome of the Master's Thesis is encapsulated in the presented hull design, aimed at achieving improved seakeeping behaviour.

Table 15: Main Dimensions final design

	Series 65	Final Design
Loa	22 m	22 m
Boa	6.86 m	6.46 m
Draft	1.15 m	1.18 m
Depth	2.9 m	3.02 m
Weight	45 tonnes	45 tonnes
LCG	9.25 m	9.04 m
GM	1.79 m	1.57 m



(a) Series 65 as reference for the L- and M-class

(b) Final design

Figure 35: Comparison of probability of exceedance between Series 65 and Final design

9.1.2 Conclusions

An evaluation is still required to determine whether the primary goal of this Master's Thesis was achieved. The stated goal was to deliver a new hull design for the tenders of 'het Loodswezen' which will reduce the vertical accelerations caused by waves compared to the currently used L- and M-class tenders. However, no direct comparison between the new hull design and the L- and M-class was conducted during this project. Although budget was allocated for such a study by Marin, it was decided not to pursue this analysis at this stage. The primary reasons for this decision include the conceptual nature of the new design, such as the unknown location of the CoG and the unfinished fairing of the hull, and time constraints, as Marin had not yet scheduled this study, leading to potentially long delays of this thesis. These considerations are further discussed in the next chapter.

Despite this, a conclusion can still be drawn whether or not this goal is achieved based on an analysis of the subquestions presented in the introduction.

The first subquestion posed was:'Which width is the is the optimal trade-off between a safe and efficient mode of operation and a high L/B-ratio?' Addressing this subquestion led to the determination of an optimal width of 6.46 metres for the 'Tender of the Future'. This width achieves a reduction of approximately 10% in peak vertical accelerations while maintaining an acceptable level of safety when compared to the current L- and M-class tenders.

The second subquestion, 'To what extend can the bow and hull be modified to reduce peak vertical accelerations, without compromising the current mode of operation?', was addressed through an iterative design process. The primary focus was on minimising peak vertical accelerations, while also considering the operational procedures and hydrodynamic resistance. To evaluate each design, two benchmarks were established. The Series 65, representing an upper bound, is a standard planing hull form scaled to the dimensions derived for the ideal new hull design, yielding peak vertical accelerations at the bow of 73 m/s^2 in sea state 4. The second benchmark, the Stan Pilot 2205 from Damen, scaled to the same dimensions, demonstrated peak vertical accelerations of 48.5 m/s^2. The new hull design, as illustrated in figure 35, achieved peak vertical accelerations at the bow of 56.2 m/s^2, which indicates a reduction in the peak vertical accelerations.

In order to evaluate the combined impact of both analyses, the vertical accelerations of the final design should be compared to a standard planing hull representing the L- and M-class tenders. This is done in figure 35, in which the Series 65 with width 6.86 metres represents the M-class tender. It is calculated that the final design reduced the vertical accelerations by 27.8%.

The goal of this Master's Thesis was not only to reduce vertical accelerations but also to develop a hull design suitable for the new tenders of 'het Loodswezen'. This means the design must align with the operational requirements and objectives set within the 'Tender of the Future' project. Therefore, the following subquestions were addressed:

- To what extend can the bow and hull be modified to reduce peak vertical accelerations, without compromising the current mode of operation?
- What mechanisms or design concepts could be implemented to mitigate the drawbacks of a AXE bow-like hull design?
- Can the deck be shaped in such a way that the drawbacks towards the operational procedure are minimised while the flare in the bow is significantly reduced?

As previously mentioned, the first subquestion was addressed with careful consideration of the operational procedures. This was achieved by widening the deck at the bow. The second subquestion was tackled through additional research ino the incorporation of a bow rotor to enhance manoeuvrability. The operational compatibility was further explored by addressing the third subquestion: specifically engineering the deck layout to support angled sailing. Figure 30 demonstrates that the proposed design maintains the operational methods currently employed by 'het Loodswezen', ensuring no compromises in functionality. Based on these considerations, it can be concluded that the new hull design is feasible for a future tender of 'het Loodswezen', as it preserves the operational procedures.

A last key objective of the 'Tender of the Future' project is to reduce fuel consumption, as it directly impacts emissions and the feasibility of certain alternative fuels. This priority was addressed in two significant ways during the design process. First, the hull was designed using the initial weight of the Mira, excluding the ballast that was added to improve comfort. This reduction in weight inherently decreases fuel consumption. Second, efforts were made to minimise drag throughout the iterative design process. Features such as a hard chine and spray rails were incorporated to release water more efficiently and preventing it from rising along the hull. This approach effectively reduces drag and, consequently, fuel consumption.

Based on the presented analyses and evaluations, it can be concluded that the primary goal of this Master's Thesis has been achieved: a new hull design for the tenders of 'het Loodswezen' has been developed. This design ensures that the current mode of operation remains uncompromised while the onboard comfort is enhanced by reducing the peak vertical accelerations with 27.8%.

9.2 Further Research

As explained in the previous section, the main goal was to reduce the vertical accelerations compared to the L- and M-class. However, such a direct comparison was not conducted. Initially, this comparison was planned, with a budget allocated by 'het Loodswezen'. The L- and M-class tenders had been previously analysed by MARIN and the intention was to apply the same methodology to the new design. However, after a thorough assessment of the associated costs and benefits, it was decided to cancel this analysis, as outlined in the conclusion. For a fully justifiable comparative study, further development of several aspects of the concept design will be necessary.

First of all, the hull design remains at a conceptual stage. Since the research focused on the hull rather than the complete vessel design, it was not yet possible to determine the CoG. The CoG depends on the integration of all systems within the hull, and by extension, the entire vessel. As discussed, the LCG significantly impacts vertical accelerations. Therefore, before undertaking the comparative analysis, the entire vessel design must be developed, ensuring meticulous placement of all components to position the LCG in a location that minimises vertical accelerations, as outlined in the discussion.

Additionally, the hull has not yet undergone the fairing process. Hull fairing is a precise and resource-intensive procedure, requiring substantial financial and time investments. Specialised companies charge significant fees and require considerable time to fair a hull. Consequently, this step was beyond the scope of this Master's Thesis, as a concept design was developed and the resources were not available. While fairing has minimal impact on vertical accelerations, it plays a crucial role in reducing resistance, which will be calculated and analysed in the comparative analysis.

In chapter 7, the introduction of overhangs during the final iteration was discussed. These overhangs were proposed to enable sailing at an angle to cargo vessels. However, the optimal operational angle for these overhangs remains undetermined and requires further study or observational analysis. This angle will influence the design and placement of the overhangs, which, in turn, will affect vertical accelerations. Determining this operational angle is essential before proceeding with the comparative study.

Lastly, resistance optimisation requires further exploration to support the goals of the 'Tender of the Future' project, which emphasises fuel efficiency and emissions reduction. While resistance was considered during the design iterations, Fastship simulations only accounted for a chine or one spray rail, limiting the scope for detailed resistance improvements. As resistance is pivotal to fuel consumption and therefore emissions, it should be thoroughly evaluated in further design stages, before performing the comparative study by MARIN.

Once these element are further refined, it is highly recommended that 'het Loodswezen' proceeds with the planned analysis of the concept design by MARIN. A finalised design would enable the precise determination of the CoG, incorporation of a fully faired hull, a completed deck design and sufficient time for the MARIN study. Additionally, the allocation of budget for this comparative study serves as a strong incentive to carry out the analysis.

This MARIN analysis would yield valuable insights into the comfort experienced by crew and pilots, a critical concern with the existing tenders. It would also provide a detailed evaluation of the performance improvements offered by the new tender design. Such insights would allow 'het Loodswezen' to assess the return on investment and determine whether the proposed design enhancements justify the associated costs.

Additional Research: Hydrofoils

Hydrofoils are a well-known solution for improving comfort and reducing the energy consumption of fast vessels. Often referred to as the most obvious choice for enhancing seakeeping behaviour at high speeds, as illustrated in Figure 36. A quick scan through the literature already gives a good impression of the pros and cons of this feature. However, the available research does not provide sufficient information to make a definitive recommendation on the use of hydrofoils for a pilot tender. Therefore, further investigation into the characteristics of a foiling tender has been conducted. This research is elaborated in this section and a suggestion will be formed on whether or not to incorporate hydrofoils into a pilot tender. Ultimately, the decision to adopt this recommendation lies with 'het Loodswezen'.

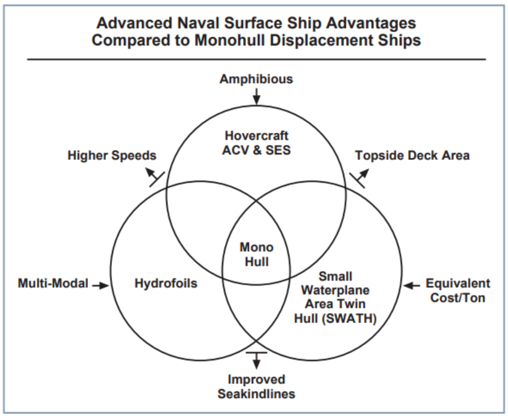


Figure 36: Comparison of the advanced marine vehicles ([4])

Since the main focus of the Master's Thesis is developing a new hull-design for the tenders of 'het Loodswezen', the research into whether or not to incorporate foils will be concise. As stated before, some information was already gathered by means of a literature research, however, the information was general for the maritime industry and not all focused on pilot tenders, which made the available research insufficient. Therefore, two companies, namely Flying Fish and Artemis Technologies, were consulted in order to gain an insight in the potential risks and mitigation strategies of hydrofoils. Flying Fish is a company which is applying its expertise in hydrofoils, electric propulsion and data processing with the main focus on sustainable, high-tech maritime solutions by the use of simulations and programming. Artemis, on the other hand, has the mission to lead the decarbonisation of the maritime industry through the design and development of vessels that produce zero emissions in operation and by this, have already delivered several electric vessels equipped with hydrofoils.

Primary advantages of hydrofoils

To begin, a brief overview of the main advantages of hydrofoils, as discussed in literature, will be presented, since these benefits are widely applicable to various types of vessels. The two primary advantages are a reduction in energy consumption and a decrease of vertical accelerations at higher speeds. For instance, a new pilot tender weighing 45 tonnes and cruising at 28 knots can achieve an estimated energy saving of 26 percent, as calculated by Flying Fish. It's important to note that this number is derived from typical planing vessels and not specific to the operational scenario of 'het Loodswezen', in which the tender decelerates regularly to 8 knots during pilot transfers. While the exact energy savings may vary slightly, it suggests that the energy consumption could be reduced with approximately a quarter.

The primary focus of this research, however, is to improve the seakeeping behaviour of the pilot tenders by reducing the vertical accelerations in waves. According to von Schertel [22], hydrofoils offer the greatest riding comfort among high-speed watercraft. Figure 37 illustrates that fully-submerged hydrofoil vessels experience mean vertical accelerations of around 0.1g at 45 knots, compared to planing vessels which endure up to 4g at 30 knots in the same relative wave height of 0.3. However, some limitations in this study should be noted. As the study focuses on mean accelerations and does not account for potential peaks; for example, a small control system error in the hydrofoil system could cause a significant increase in vertical acceleration. Additionally, Von Schertel states that the hydrofoil and planing craft could not be compared in offshore conditions in his research, implying that his findings, shown in figure 37, could not fully apply.

Despite these limitations, insights from Von Schertel's research, along with discussions with Artemis and Flying Fish, indicate a considerable reduction in vertical accelerations with hydrofoils compared to planing vessels. This is largely because hydrofoil vessels operate with their hull fully elevated above the water surface, minimising the waterplane area to slender struts. The same concept of minimising the waterplane area is also seen in SWATH (Small Waterplane Area Twin Hull) vessels, which is also a promising option to improve the seakeeping behaviour according to figure 36.

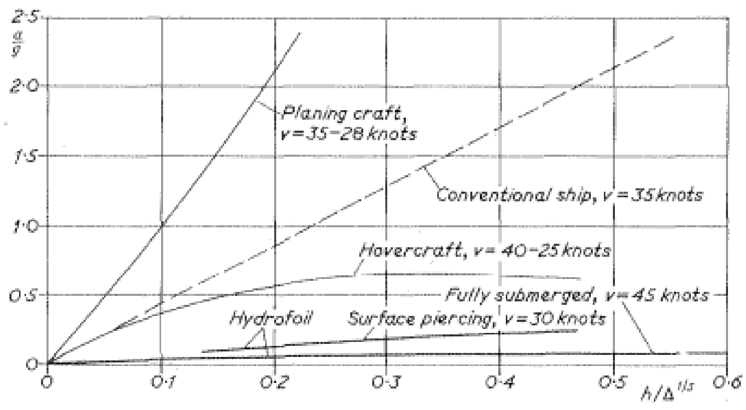


Figure 37: Induced vertical mean accelerations vs. relative significant wave height

Challenges and risks

Hydrofoils seem a promising option for 'het Loodswezen', though, it is essential to keep a critical view on the existing literature and research, given the unique operational purpose of pilot tenders. To gain a better understanding of these specific risks and challenges, Artemis and Flying Fish were consulted.

A first concern is the safety of both pilots and crew. As previously mentioned, there is a small risk of crashes due to malfunctions of the control system or hardware damage. Both companies were asked to assess the risk of such incidents. Flying Fish stated that these events are rare, but do occur, and therefore seatbelts should be mandatory to ensure pilot and crew safety. They believe that additional safety measurements besides seatbelts are unnecessary. Furthermore, it is worth noting that regulations for foiling tenders which can carry up to 12 passengers are limited, leaving safety protocols largely to the responsibility of users. This helps to explain why Artemis has not implemented seatbelts in their tenders. They argue that no extra safety measures are needed and that the safety of pilots is not compromised, partly because they have not tested their tenders in severe offshore conditions. However, they acknowledge that their point of view could change after testing in harsher sea conditions.

Another key aspect of safety is evaluating the structural integrity of the struts and foils and considering mitigation strategies. Both companies use similar methods to protect the hull from damage if the struts are hit by an object, primarily through the design of break-points in the foils and struts. For example, Artemis incorporates three break-chains in their designs:

- Break-point at foil-strut connection: If the foil is hit by an object, this break-point will ensure that only the foil shears off, preventing further damage.
- Break-chain in the strut: Located mid-strut, this allows only the lower part of the strut to break off, leaving the hull and upper half intact.
- Break-chain just below the hull: If an impact occurs in the upper half of the strut, it breaks off just beneath the hull, preventing the hull for taking damage.

These features indicate that adding hydrofoils does not increase the risk of hull damage. Furthermore, any damaged foils or struts can quickly be replaced, allowing tenders to return in operation with minimum downtime, according to Artemis. Although this solution is straightforward, a more advanced alternative is also available: a hydraulic system that retracts the struts on impact. In this way, the risk of damage is minimised and replacement costs are reduced. The questions remain about the force limit such a hydraulic system can withstand and the force thresholds for activation. Flying Fish emphasised that these specifications should be defined by the users of the tenders and based on the FMEA.

If a strut breaks off, the consequences could be beyond replacing it, as the propulsion system would also be at risk. Since the hull is elevated above the water surface, the propulsion system is typically fitted entirely in the struts. As a result, the complete propulsion system could be lost in case of severe damage. For a pilot tender operating near large cargo vessels, this could lead to critical situations. Currently, fast tenders with hydrofoils are either equipped with waterjets or propellers, which carry different risks when a strut breaks off.

In the case of propellers, both the motor and propeller are fitted in a pod at the end of the strut. If the strut breaks off, the entire propulsion system could be lost. Fortunately, the tenders of 'het Loodswezen' are equipped with two engines and two propellers, allowing the crew to return safely to port, even if one propulsion system fails. However, this would lead to suspension of the operations until the spare tender will be deployed.

With waterjets, the potential impact is less severe. The engine and impeller are still located inside the hull, operating the tender will still be possible even if a strut breaks, as water can still be drawn into the impeller. Flying Fish noted that waterjets are already widely used in high-speed tenders. On the other hand, Artemis, which specialises in small electric tenders, argue that waterjets consume too much energy for their electric propulsion system and are too challenging to incorporate in hydrofoil designs. Furthermore, they claimed that if strut damage is severe enough to affect the propulsion system, the crew will be likely to return to port, just like they would with serious hull damage.

The primary focus of this Master's Thesis remains the reduction of vertical accelerations in waves. As seen in figure 37, hydrofoils could substantially increase the operability of fast vessels. However, some questions arise regarding the seakeeping behaviour, given the limited length of the struts. For instance, Artemis' commercialised tenders have struts which allows the user to foil up to a significant wave height of 1.5 metres, after which the hull can no longer remain fully elevated above the watersurface. This limitation is quite problematic for 'het Loodswezen', as they experience severe slamming at wave heights between 1.5 and 2.5 metres. Nevertheless, Artemis suggests that the foils could also improve the seakeeping behaviour by damping the vertical accelerations in waves by means of foil-assisted planing. Flying Fish also supports this approach, arguing that foil-assisted planing might be the optimal solution for 'het Loodswezen' in order to reduce the energy consumption and vertical accelerations.

However, the statement that foil-assisted planing will improve operability is hard to evaluate. Currently, there is limited data on the performance of foil-assisted vessels operating in sea state 3 of higher. Artemis still has to test their tenders under such conditions and available literature primarily covers sea states 1 and 2, as seen in studies by Mejia Jaramillo et al. [23] and Suastika et al. [24]. Furthermore, these studies report different outcomes: Mejia concluded that hydrofoils lifting 80 percent of a catamaran's weight can reduce the mean vertical accelerations with 55 percent in sea states 1 and 2, while Suastika observed only a reduction of 9.7 percent if the foils lift 40 percent of the catamaran's weight. Next to this, it can be argued that foils may not be able to counteract the peak vertical accelerations of sudden severe wave impacts [25]. By this, it can be concluded that mean accelerations could be reduced, but that the operability and seakeeping behaviour is not improved. As Keuning explained that crew perceptions of seakeeping behaviour are mainly influenced by these high peak impacts, instead of mean vertical accelerations [11]. Consequently, the current data on foil-assisted planing is too inconsistent to draw objective conclusions on the seakeeping improvements, showing that the real-life tests of Artemis' pilot tenders in higher sea states should be awaited.

A last significant challenge with hydrofoils is the high associated costs. Each vessel design requires a custom design of its hydrofoils, which leads to higher engineering costs during the design-phase of a new tender. Additionally, manufacturing foils is costly due to the extremely smooth and precise foil surfaces that are required, which asks for specialised fabrication techniques. These surfaces, along with the systems for the operation of the hydrofoil system, also demand frequent maintenance, leading to higher operational costs as well, not to mention potential costs for the replacement of damaged struts. All these high costs are one of the reasons why few foiling vessels are being built [26].

In order to gain a comprehensive overview of all the costs related to hydrofoils, a full life cycle assessment would be required. However, this process is intensive and is thus beyond the scope of this research. Therefore, the following section will provide a conclusion and recommendation regarding the implementation of foils in new tenders, purely based engineering considerations, focusing on safety and performance of hydrofoils.

Recommendation towards the use of hydrofoils

'Het Loodswezen' is currently working on the development of the 'tender of the future'. In this project, two primary objectives are to reduce the emissions of their tenders and to improve onboard comfort. Hydrofoils offer promising solutions for both goals, as previously discussed. They can potentially reduce energy consumption by approximately 25% (even much more with a lighter tender) and significantly decrease vertical accelerations, improving comfort.

However, there are several challenges that impact these benefits. First, the reduction in vertical accelerations is limited to specific wave heights due to the limit on strut length. For example, Artemis has tenders of which the struts enable foiling up to a wave height of 1.5 metres. Additionally, literature show inconsistent results regarding the effectiveness of foil-assisted planing and Artemis did not conduct tests yet, making the exact benefit of foils on seakeeping uncertain.

Moreover, the use of hydrofoils increases the risk on damage. This is not only due to the potential for foils to collide with the hull of a cargo ship during the pilot transfer process in rough conditions, but also because additional mechanical components and software are required. Damage to foils and strut could lead to propulsion failure or even a loss of it, which would pose safety risks and cause significant delays in the pilot schedule, impacting operations.

A further challenge for 'het Loodswezen' is that their tenders are relatively heavy and required to carry up to 12 passengers. Artemis has indicated that they are not equipped to produce a foiling vessel of this scale. Therefore, should 'het Loodswezen' choose to incorporate tenders in their design, they would have to re-evaluate and adapt their current operational process, resulting in a time-consuming and costly project.

Finally, the high operating and investment costs associated with hydrofoils would significantly increase the financial burden of the fleet.

Considering these factors, the uncertainty regarding the seakeeping behaviour of foil-assisted planing vessels, the increased risk of damage, the need for a complete operational overhaul and the high costs involved, the conclusion is drawn that implementing hydrofoils in tenders of 'het Loodswezen' is not the optimal solution for the 'tender of the future', with the emphasis on 'the tender'. A valuable option could be to incorporate foils for only a part of the fleet, operating in the North of the Netherlands, where the tenders have to sail large distances in relative calm waters. All these aspects taken in consideration, it seems not feasible to incorporate foils in the whole fleet.

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Appendix A

Input code for Fastship simulation

```
0.1     0.002   0.002   0.002   0.1     0.002   0.002   0.002
45      1.18    8.93    2.10    1.59
3.23    5.50    0       2.42
1.33    1.761   0.614   1       0
20000   0       0
0.00
28
0.1964  0.18    2.06    1.12    2.67    2.9
0.7857  0.16    2.11    1.12    2.76    2.9
1.5714  0.14    2.15    1.12    2.84    2.9
2.3571  0.12    2.19    1.12    2.92    2.9
3.1428  0.10    2.24    1.12    3.00    2.91
3.9285  0.08    2.28    1.12    3.08    2.91
4.7142  0.06    2.32    1.12    3.14    2.91
5.4999  0.04    2.36    1.12    3.20    2.92
6.2856  0.03    2.40    1.12    3.25    2.93
7.0713  0.01    2.43    1.12    3.28    2.94
7.857   0.00    2.44    1.12    3.30    2.96
8.6427  0.00    2.44    1.12    3.32    2.98
9.4284  0.00    2.42    1.13    3.33    3.00
10.2141 0.00    2.38    1.14    3.33    3.03
10.9998 0.00    2.32    1.16    3.30    3.05
11.7855 0.00    2.25    1.19    3.27    3.08
12.5712 0.00    2.17    1.21    3.23    3.10
13.3569 0.00    2.08    1.25    3.18    3.13
14.1426 0.00    1.96    1.29    3.12    3.16
14.9283 0.00    1.81    1.34    3.02    3.20
15.7140 0.00    1.63    1.39    2.89    3.24
16.4997 0.00    1.44    1.45    2.75    3.29
17.2854 0.00    1.23    1.51    2.58    3.33
18.0711 0.00    1.01    1.57    2.38    3.39
18.8568 0.00    0.78    1.63    2.12    3.45
19.6425 0.00    0.55    1.69    1.75    3.52
20.4282 0.01    0.31    1.75    1.27    3.58
21.2139 0.10    0.04    1.80    0.49    3.65
22.00
1       1       1       1       1       0       1
9.26    0.00    0.00    0.00
0.00    -0.064    5.00     0.00
0       0
0       1000
0.10    0.05    0.00    0.05    0.05
5       19.8
```

Appendix B

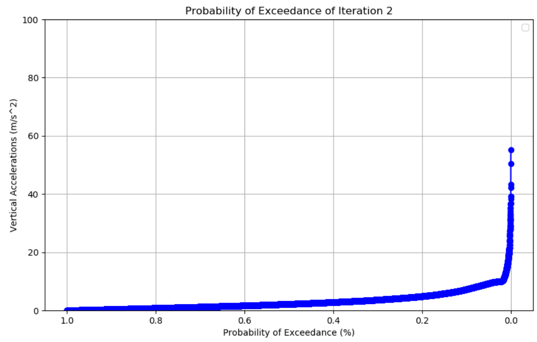
Code for the Jonswap spectrum for: Tp = 6s, H1/3 = 2.25m and a forward vessel speed of 18 knots

```
           60
0.101139115      0.819279303      0.068421873      5.119059896
0.101166148      0.855311821      0.074572713      5.69125859
0.101144507      0.882191903      0.079333594      0.797881698
0.101183638      0.903949146      0.083295011      5.738909759
0.101134683      0.922066168      0.08666728       3.973230325
0.101250456      0.937390567      0.089571975      0.61286444
0.101150819      0.950522114      0.092099112      1.749855917
0.10121826       0.96192828       0.094322733      3.436157926
0.101196756      0.97199192       0.096306656      6.01619288
0.101255099      0.980998709      0.098099742      6.062573467
0.101319922      0.989181261      0.099743075      0.990312199
0.101279789      0.996704774      0.101266096      6.098414306
0.101210474      1.003696208      0.102691751      6.014057306
0.101365455      1.010276754      0.104042724      3.049705145
0.101234433      1.016530003      0.105334684      5.028310484
0.101295844      1.022520599      0.106579855      0.891498158
0.101361723      1.028321198      0.107792506      2.650004294
0.101248707      1.033974973      0.108981065      5.753735997
0.101302512      1.039525892      0.110154341      4.977585453
0.101310795      1.045023359      0.11132251       6.028668716
0.101278924      1.050502787      0.112492977      4.120140326
0.101303116      1.055996431      0.113672626      0.224383094
0.101302519      1.061531111      0.114867309      5.335236779
0.101246064      1.067129308      0.116082055      5.868452651
0.101312501      1.072823317      0.117324146      4.264618752
0.101310462      1.078644988      0.118600919      4.761021655
0.101182651      1.084615923      0.119917604      4.669239005
0.101385385      1.090785727      0.12128578       2.464435046
0.101180505      1.097190337      0.122714234      4.118489049
0.101373446      1.103878266      0.124214804      1.075597682
0.101222631      1.110908334      0.12580197       4.436218406
0.10120556       1.118332137      0.127488967      0.200011673
0.101304784      1.12624634       0.129299778      1.73995843
0.101243027      1.134741648      0.131257758      0.290103403
0.101231147      1.143921976      0.133390162      0.610296981
0.101311877      1.153934373      0.135735427      5.173938128
0.101185685      1.16492482       0.138333317      4.365736995
0.101216392      1.177069888      0.141232775      1.992394794
0.101251366      1.190588515      0.144495516      5.970421216
0.101169673      1.205671944      0.148179902      0.216431107
0.101213402      1.222510887      0.152347897      2.756712114
0.101212255      1.241260114      0.157056745      2.397402491
0.101206501      1.261988776      0.162346144      4.809883836
0.101217564      1.284713201      0.168245465      4.996388335
0.101228529      1.309421458      0.174779261      1.174155203
0.101248388      1.336128073      0.181981471      3.077280456
0.101248322      1.364922552      0.18990964       2.799700669
0.10124739       1.396007239      0.198658126      4.060904409
0.101249046      1.42972456       0.208370267      4.457070683
0.101252408      1.466568711      0.219248092      4.741836272
0.101246135      1.507209854      0.231567945      1.734316708
0.101235054      1.55255527       0.245711301      4.270697872
0.101226889      1.603867639      0.262221346      4.116102153
0.101206209      1.662951848      0.281896926      1.021719665
0.101187745      1.732521116      0.305976495      0.747684484
0.101142689      1.816899187      0.336505877      3.131313689
```

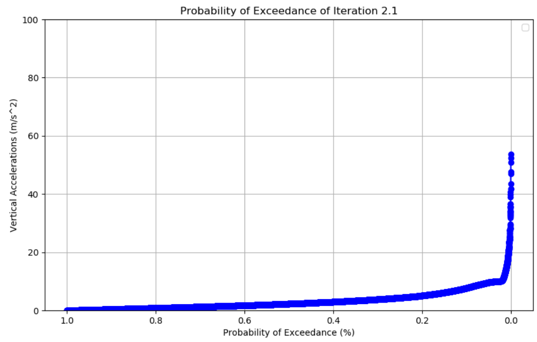
```
0.101074125      1.92359318       0.377187637      6.030249139
0.100920478      2.067357307      0.435674438      2.138706597
0.10050673       2.283813241      0.531682255      3.677345734
0.09853875       2.707652651      0.747337704      1.40625189
```

Appendix C

In the figure below, the probabilities of exceedance are depicted of Iteration 2 and Iteration 2.1. The only difference between both designs is the height of the chine relative to the keel. In iteration 2 and 2.1, the height of the chine is respectively 1.32 metres and 1.12 metres, (5 cm below the waterline).



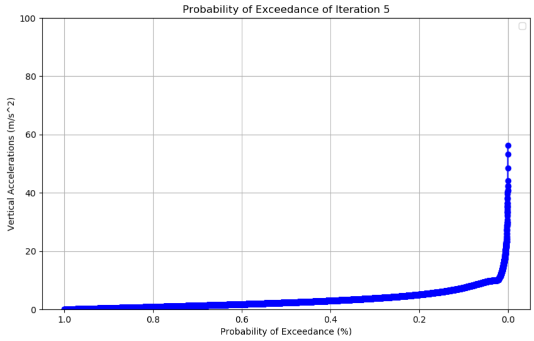
(a) Probability of exceedance of Iteration 2



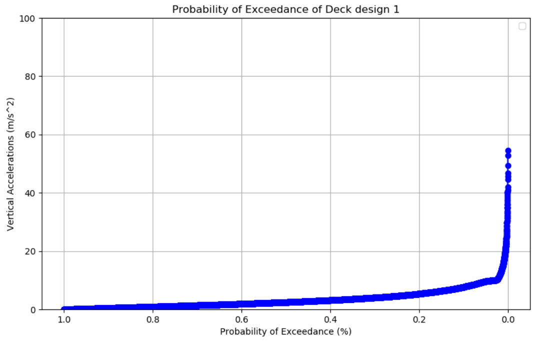
(b) Probability of exceedance of Iteration 2.1

Figure 38: Comparison of vertical accelerations between iteration 2 and iteration 2.1

Appendix D

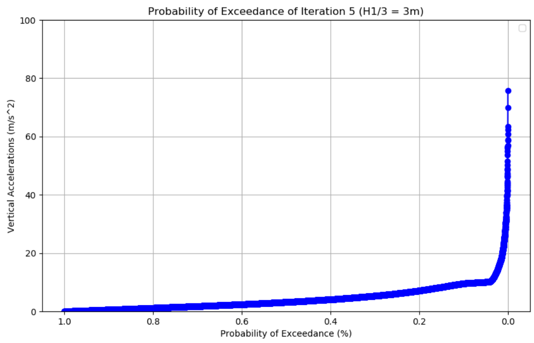


(a) Probability of exceedance of iteration 5

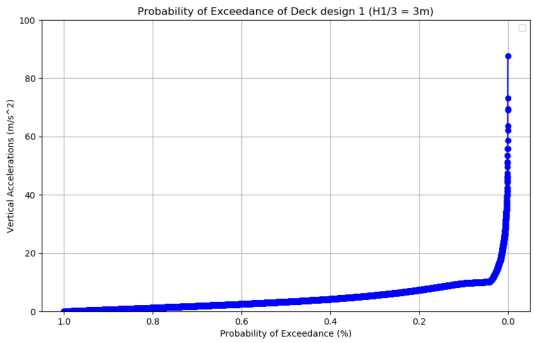


(b) Probability of exceedance of deck design 1

Figure 39: Comparison of vertical accelerations between iteration 5 and deck design 1 ($H_{1/3}$ = 2.25m)



(a) Probability of exceedance of iteration 5

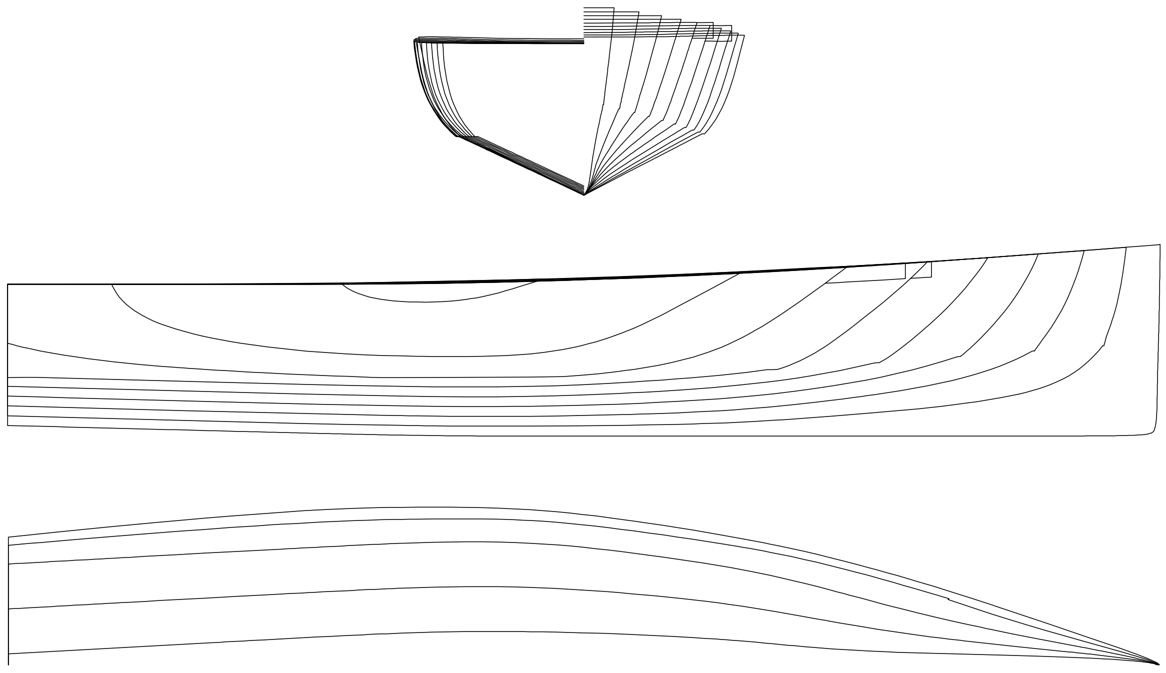


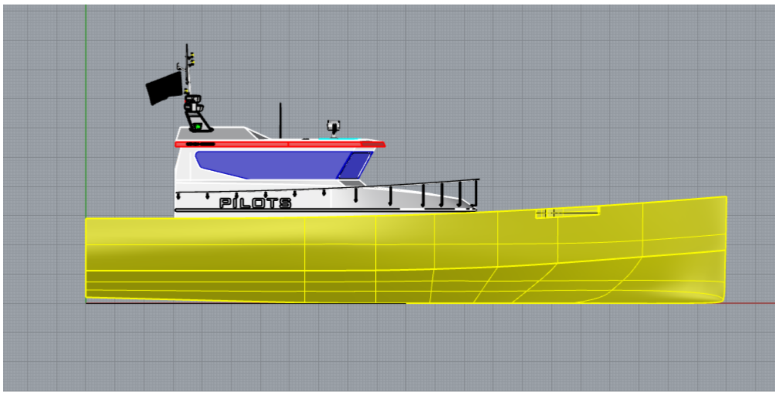
(b) Probability of exceedance of deck design 1

Figure 40: Comparison of vertical accelerations between iteration 5 and deck design 1 ($H_{1/3}$ = 3m)

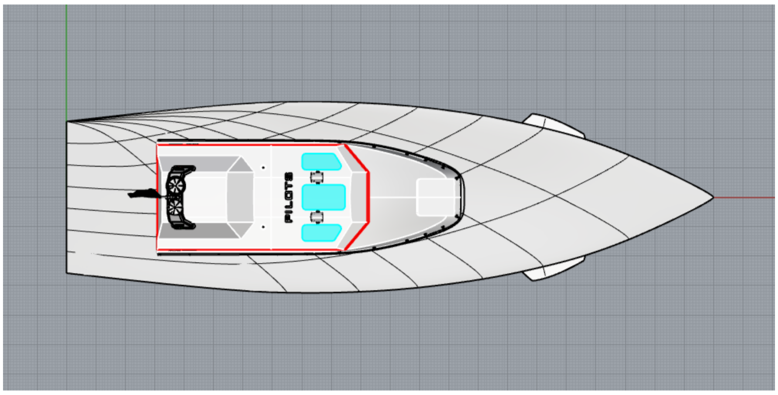
Appendix E

Lines plan of final design.

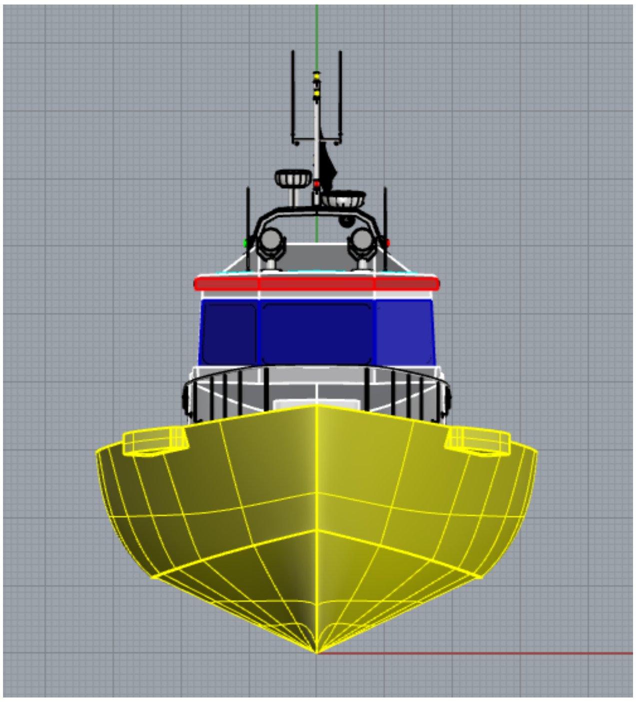




(a) Side view



(b) Top view



(c) Front view

Figure 41: Final Design