Design of a Low-wash Inland Patrol Boat

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Master Thesis

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ABSTRACT

This project is designed with a goal to develop a preliminary design phase project of a police patrol boat for the needs of the Directorate of Maritime and River Police (SPN), Belgium. The authorities have issued a list of constraints that define the project, and have been used as guides throughout the development.

To accommodate all the requests set by operators, this study, in its early phase, concentrates on a hull form design with assessment criteria being:

- Minimizing the wave wash heights, addressing the physical impact on the environment
- Minimizing the hull resistance and by that lowering the environmental pollution,
- Obtaining maximum amount of high-quality space, for benefit of day to day, operating.

Several hull designs are assessed by above criteria using computational test methods. The comparison is made on the basis of Neuman-Michell potential flow theory embedded in commercial software, which provides results accurate enough to yield a rugged final hull design and a set of characteristics that significantly influence hull performance. These features are fine-tuned in CFD software relying on unsteady RANS equations for results with a much higher order of accuracy.

Wave heights and resistance of final design measured between two computational approaches are in good accordance, with wave wash height up to 40% lower when compared to starting models and reference boats.

The general arrangement, capacities, as well as function diagrams, are developed between two main criteria:

- Adaptation to existing hull,
- Maximizing functionality, in a sense of safer faster and easier response by the crew.

The design is such that it can accommodate a variety of potential usage profiles and variety of propulsive systems. Great attention is devoted to achieving a distribution of weight that would ensure a minimal change of trim, providing for constant wake characteristics. Finally, electrical analysis and analysis of boat stability are conducted as per classification rules and requirements.

The final product is a balanced, comprehensive design for a patrol boat that offers solution to all posed chaleges. Inland oriented design, with possibilities to stand up to the waves up to two meters high give it great usability rating. Environmentally and safety friendly it is a good choice for narrow waterways of high frequency. Easy to work on and designed to be reliable at low–cost operating regime, it is a good replacement for the vessels currently in use.

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1. INTRODUCTION

The thesis in front of you represents an answer to the challenge of designing a new breed of patrol boats. These vessels, adapted for the 21st century can fulfill all the tasks as their predecessors but in a way that is much more compatible with the problems of time we live in.

- Safe
- Environmentally responsible
- Functionally optimized
- Ergonomic
- Efficient

Project developed in company DN&T, based in Liege, Belgium is a respond to all of the above conditions, as well as some more specific for this particular boat, set by the Directorate of Maritime and River Police (SPN) of Belgium. The requirements standing, also include:

- Boat type: Inland navigation vessel
- Possibility of navigating in estuaries and coastal areas
- Hull type: Monohull
- Length overall: 11-16 m
- Maximum beam: 6 m
- Required speed: Operating 8-12 km/h; Maximum 30 km/h
- Vessel needs to comply with all rules and regulations applicable, with absolute priority on reducing environmental impact

All these requests and recommendations come from an extended evaluation period performed on old vessels and a wish to fix some of their deficiencies.

To summarize, commissioned boat is to be a patrol vessel used by the police. This represents challenge by itself since the boat will be used for fast response operations. Simultaneously, the boat could be utilized as a rescue vessel for both helping other boats and helping individuals in water. As it is representing police, and so forth the country, it needs to lead by example in the aspect of safety and environmental issues.

1.1 Problem Description

From the summary above it is easy to conclude that the thesis, or the design of the boat, needs to address two major families of problems:

- Safety of other users of waterway and ecological issues, arising from the boat impact on the overall environment
- Functional issues, related to multiple usage profiles and their demands

Indeed, it is noticeable that existing designs, regardless of them being semi-displacement or planning, create strong waves when moving at the top of their respectable speed range. Since the potential of the wake impacting safety or environment depends a lot of the physical properties of the waterway, as discussed in „Guidelines for managing wake wash from high-speed vessels“ (MarCom, 2003), these issues are especially important in rivers and estuaries since the waves do not have time to dissipate.
The problem arising from this is three-folded:

- Created high waves are a nuisance and even a danger to other users of inland waterways, especially narrow ones. Moored vessels, as well as vessels under way, may experience strong motions, change course or even suffer damage when subjected to extremely high waves.
- Same waves instigate erosion of water banks, and as such irreparably change the ecosystem. Furthermore, this phenomenon can produce unwanted costs for the state then needs to invest in protecting these banks.
- Finally, but not the least important, the waves created increase the resistance in a vessel, and not only the vessel creating the waves, but all other moving through the wave field, and instantly increase fuel and oil consumption, making an immediate and irreparable effect to the atmosphere.

Further on, the nature of boat purpose imposes strict design criteria. Patrol boats have been built in countless iterations, and the only conclusion is that every needs to suit its particular requirements since the range of usages is so broad. Operations on the water can be quite risky, and it is a duty of naval architect to simplify sometimes complicated and tedious tasks.
Space requirements on this type of vessel are high, in order to provide needed autonomy, wide radius of speeds and unconstrained access for quick servicing. In a 15 meter boat, this means

that combined functional spaces are of high importance, as well as their connecting in a direct way, and not through a series of space-wasting corridors.

This brings up a matter of verbal communication on board since crew members need to be able to do it in high-stress situations. It yet again defines a need of having a lot of spaces in an area small enough for uninterrupted communication.

The third restriction on zones and their interconnectivity comes in a form of open space. This means that any obstacle, like stairs individual steps, rails, guards and so on, need to be taken to an absolute minimum.

As all excessive motions are unwanted, the spatial organization has to ensure minimum motions in spaces essential for crew functioning. Keeping the motions at a minimum in, sometimes, rough waters is not a simple task and need to be addressed from the start of the design process. Again, river environment has challenges of its own. Anchoring and mooring in perpetually moving water are challenging, especially from the fact that vessel must be able to be anchored facing downstream.

1.2 Possible Solutions

Having the problems in two big groups does not always mean that there are only two options. Luckily, since these problems are in families, often one solution can resolve more than one problem. On the other hand, some problems require opposite solutions. In those cases it is only possible to find the best compromise between the two. Ergo, Pareto frontier must be created, losses and gains from both sides evaluated, and the solution will always apply to a particular instance.

As a first problem, wake waves have been defined. This complex issue has been a topic of many papers and thesis and has many solutions, some of which are obvious and some less so.

The main question to ask at this point is "Who?" meaning who is responsible for the waves impact on safety and environment. The answer gives sense to the multiple solutions.

- Waterways authorities may prevent some of the problems by adapting the topography of banks, introducing wave dampers or even as little as posting warning signs
- Companies and individuals navigating the waterways can change operating habits, e.g. cruising speeds or even routes to avoid causing issues
- Ship designers are to design the vessels in such a way that minimizes any influence on people, vessels or nature.

At this point, the first task of the thesis is defined. Due to the fact that hull form is directly related to the waves created, a naval architect needs to understand the importance of generating a design that avoids excessive wake creation. This type of hull design will also have a positive effect on reducing the atmospheric emissions, since wave resistance can be up to 50% of total resistance value for some high-speed vessels, and with its reduction, reduction of fuel burned is imminent.

One more possibility of reducing the amount of gasses emitted is a fresh take on the propulsion system. Today, many companies offer hybrid or even fully electrical propulsions that can profoundly reduce boats environmental footprint, but at the cost of some other characteristics. As mentioned before, this is a question of compromise between several factors like weight, space requirements, price, servicing time, etc.

Contrary to previous, the problem of space and functionality is solely in the hands of an architect. To provide a multifunctional boat, spaces on board, both opened and closed must also be multifunctional. Any functions taking place at separate times may be assigned to same physical space and so provide law officers with a vessel that is never cramped, but just well organized.
The layout is to follow the typical workflow, or as Louis Sullivan famously said, “Form ever follows function.” In order to provide easy access, number of compartments must be minimalized, while still providing for safety minimum defined in rules and classifications. Finally, exceptional deck height will solve the problem of fast movement on board and provide enough space for people as well as for hiding structural elements that would otherwise be exposed.

1.3 Importance of a Proper Solution

As it was discussed before, and as it can be seen from many other authors like (Gadd, 1994) and (Nanson, 1994) and their references, impact of wake waves is real and all present. Even more in rivers and confined waterways, special care must be attributed to solving or at least minimizing this problem. Many other researchers investigated harmfull effects of wake, they further gave examples of problems and possible solutions, like (McRae, 1994) published by RINA are plentiful. In spite of the problem being recognized so long ago, the comprehensive solution still does not exist.

1.4 Aim of Thesis

Present thesis is a project that responds to a particular tender. By no means does it strive to provide a final and undisputable design for a patrol boat function itself, but merely to provide an “advanced preliminary design phase (as defined in Fig.1)” project that solves the needs of a single user (even though user, in this case, is a country). In the time of writing of the thesis, company in charge still had not obtained the building order, so detailed design must be postponed until detailed specification have been provided by the authorities, which provided the time necessary to yield well-thought solutions in every design step.

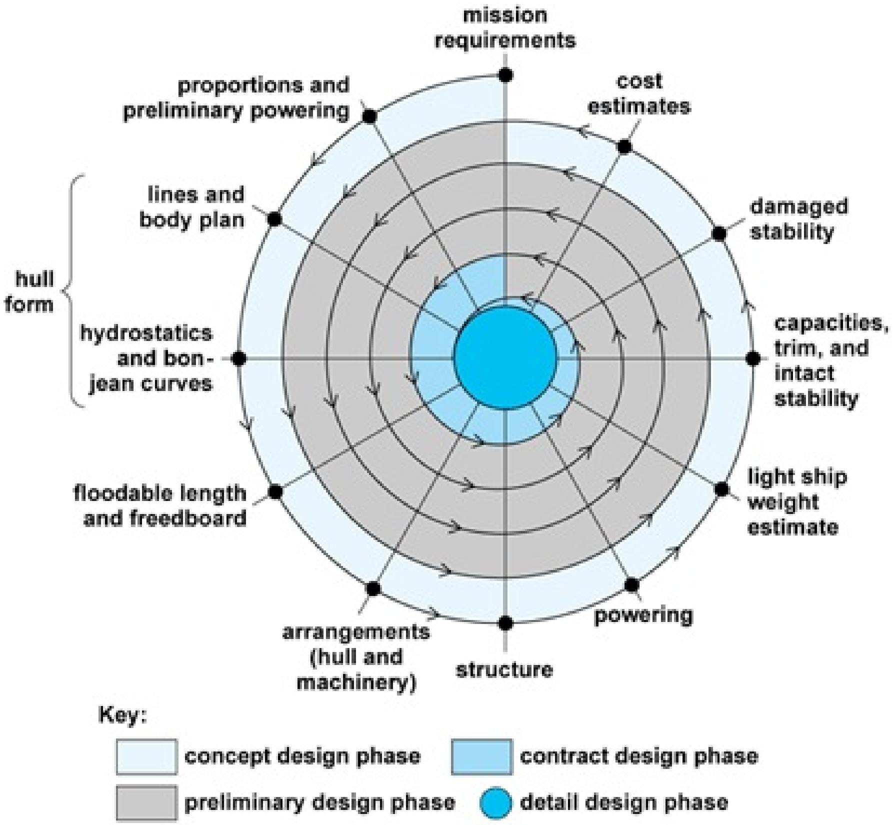

Figure 1. Ship design spiral. Available from http://www.marinewiki.org/images/c/ce/Ship_design_spiral.jpg [Accessed 28 Nov 2016].

Along with the development of vessel defined by all requirements and constraints, the thesis will, in its first part, produce a designer guide for minimizing the wake and resistance of the vessel with chronologically presented and described steps taken to create the final solution for the current problem. Again, since every vessel is unique, both in user needs and in the environment it’s in, those steps may have to be revised for some individual cases.

1.5 Methodology of Work and Thesis Structure

“Ship design is iterative, “trial and error” procedure where the final result has to satisfy certain requirements, specifies beforehand. The designer has to start with some assumptions and work through the design to see if, at the end, it satisfies the requirements.” (Lars Larson, 2000)

Through comparative analysis of existing patrol boats and their assessment in relation to criteria set by the customer, a list of properties that define „best practices” in the industry today is created. This list is then changed to adapt to some specific requirements. That is how the first, concept design was created.

Knowing all essential characteristics, the design process of a hull as potentially the most influential part of this particular build can be started. Several contending hull designs, heavily used in marine industry are produced in 3D modeling software so that leading characteristic (displacement in this case) is the same. Hulls are judged based on three criteria:

- Minimizing the wave wash heights to provide safer waterways and preserve river eco-system, which addresses the physical impact on the environment
- Minimizing the hull resistance for the purpose of lowering fuel and oil consumptions and gas emissions and by that reducing the environmental pollution,
- Obtaining maximum amount of high-quality space for day to day operations while staying within the set size limits to ease and improve the quality of everyday tasks carried out by law officers.

Comparison of this sort, conducted using fast simulations based on Neuman-Michell potential flow theory, produced data that allowed the best hull to be defined. The same type of assessment allowed for determining properties of this hull, which will when changed severely influence three judging criteria outlined above.

Finally, hull defining properties are fine-tuned in a CFD software of much higher accuracy.

Finalized hull design opened gate for the continuation of the design process started at the concept design stage. Subdivision arrangement for defined compartments is done in accordance with spatial needs and Bureau Veritas (BV) rules as per “Rules for the Classification of Inland Navigation Vessels - November 2014 edition”. The same set of rules has been used, and double checked in comparison to „Hull in Aluminium Alloys - July 2015” to define scantlings and consequently the weight of the structure.

Applying production requirements to designed vessel resulted in series of small changes, and provided the need for another design loop.

After the final definition of all characteristics, stability assessment is made to ensure rule compliance as well as safety.

2. MANAGING WAVE GENERATION

This chapter will give a short theoretical introduction to the phenomena constituting main challenges of the project.

2.1 What is Patrol Boat?

In general, patrol boat is relatively small type of naval vessel with a primary task of defending and protecting coastal or inland areas. The production and high demand started before World War I and continues to rise today. Navy patrol boats are usually somewhat smaller than corvettes, and police patrol boats range from 8 up to 40 meters.

Police patrol boats are, besides their primary role, often used as multifunction boats, carrying all the duties of the inland police. The website of Directorate of Maritime and River Police (SPN), Belgium describes those as:

- Monitoring compliance with the laws and regulations in and around the water and on board vessels.
- Border control.
- Judicial police on board vessels.
- Seizure of ships.
- Administrative police in the framework of the police water.
- Specialized support to third parties.
- Illegal immigration and trafficking
- Drugs
- Pollution
- Terrorism
- Traffic violation and accidents

A high number of potential functions calls for incredibly intricate designs at some instances, but growing number of this kind of boats in rivers makes it easier for police officers to carry out their duties.

2.2 What is Wake Wash?

Before anything else wake wash is a pollutant. According to (Yaakob, 2009), a boat created wake dominates environmental damage of inland waterways. Proofs of previous statement are numerous, and some of the reported cases are erosion of Mississipi River main channel banks due to recreational boating, levee erosion of the San Joaquin River Delta caused by river traffic and so on.

How does it work? The vessel intending to move needs power. This power is partially lost to wave making. Consequentially, moving vessel makes waves.
Wake pattern behind a boat, whether we are talking about ocean cruiser or remotely operated toy boat is only in scale, and it looks very similar to Fig. 2 under.

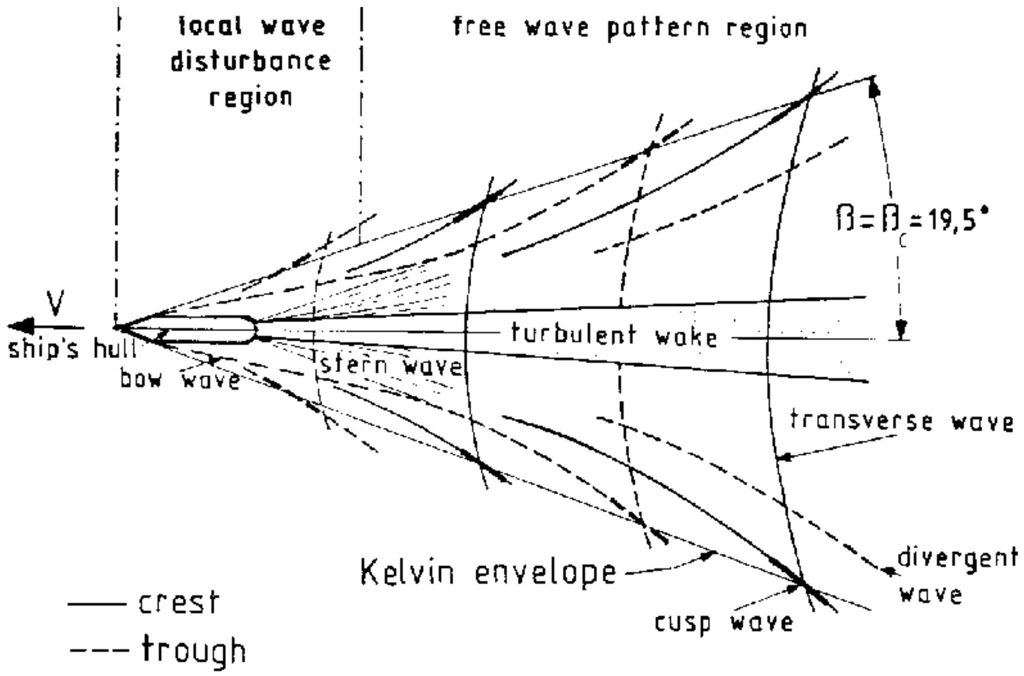

Figure 2. Wake scheme. Available from https://crisp.nus.edu.sg/~research/shipwakes/images/wakescheme2.gif [Accessed 21 Nov 2016].

As is well described by (Rožman, 2009) the wake is an intricate pattern of waves behind a vessel, primarily containing two types of waves: cusp waves that define the specific wake angle, and transverse waves located between cusp waves.
Explanation of wake pattern is closely related to knowing the dispersive nature of waves.

If water were a nondispersive domain, the angle of V pattern would be θ, defined in Fig. 3a would be formed as a result of the relation between the velocity of boat and phase velocity of waves:

$$C = V_0 * \sin\beta$$

Where C is phase velocity, and V_0 is the velocity of the boat.

Since we need to consider dispersion, we will take into account that the group velocity is half of phase velocity.

Group velocity is also the velocity of the location of the line where a full band of wavelengths created by the boat gives the highest interference. This phenomenon causes the concentration of waves at angle β of 19,5°, even though different wavelengths should provide different angles. To why this happens, look at Fig. 3b.

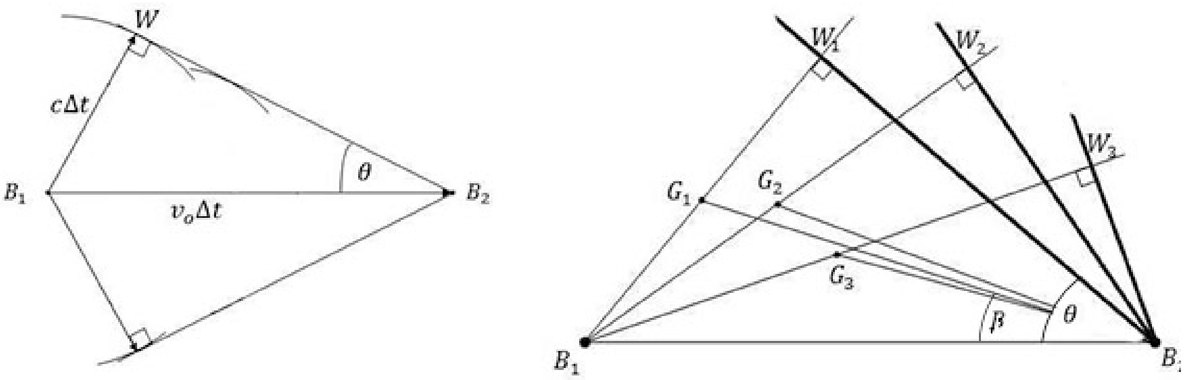

Figure 3. Non-dispersive and Dispersive wake pattern. Available from (Rožman, 2009, page 5, 11).

These, cusp or diverging waves, are a function of hull form, the angle of entry, speed, Froude number and so on. (Stumbo, et al., 2006)

The transverse waves following the boat, always seem to be at the same distance, so we can conclude that phase velocity of those waves is same as ship speed. This means that the whole pattern travels along with a boat, similarly to if it was attached to it. The radius of those waves is equal to the distance of given wave from the boat. Froude number is what defines the ratio of wavelengths between the cusp and transverse waves. The wavelength of transverse waves increases with Froude number, but at the crossing of hump speed, they disappear and give way to higher diverging waves.

2.3 What is Wave Resistance?

Wave Making Resistance is a drag on a ship hull created by waves and is equal to the energy needed to push the water out of hulls way.
Depending on the size and speed of the vessel, this component can be major or minor part of the total resistance. For smaller boats moving at relatively high speeds, this element can be up to 50% of total drag. There lays the explanation for the need for its reduction.
Some of possible ways to reduce wave creation and by that wave resistance are reduced displacement, narrow angle of entry or bulbous bow.

2.4 Hull Design in Function of Low Wake Generation

As described by (Clayton, 2013) previous work on wake prediction and managing is plentiful but due to confidential nature of hull design process in general, and especially in large enterprises, results of this work are usually not available. Thus, navigating through this field is mainly a question of trial and error.

A set of experimental results presented in the paper above (Clayton, 2013) can serve as a starting point for further development. In his work Clayton used two models, as shown in Fig. 4 and made a total of 24 runs in the towing tank, 12 with each model. This provided results that allowed assessment of some hull properties.

Figure 4. Two types of planning hulls, V and flat bottom. Available from (Clayton, 2013).

- When testing the draft influence to wake height, Clayton concluded that corresponding increase in wake height happens only in the area of the initial wake. The rest of the waves do not show any signs of being affected.
- Regarding trim, his results are very interesting. The assumption that wake is profoundly affected by the downwash (Fig. 5) proved correct in this case and yielded the following. Being that downwash caused by excessive trim produces same downward velocity of water regardless of draft, the effects of trim are much more noticeable on vessel with small draft due to the proximity of air-water interface.
- Finally, the effect of speed to the wake proved to be minimal, but this result needs to be taken with a lot of caution since the trim was completely disregarded in this case.

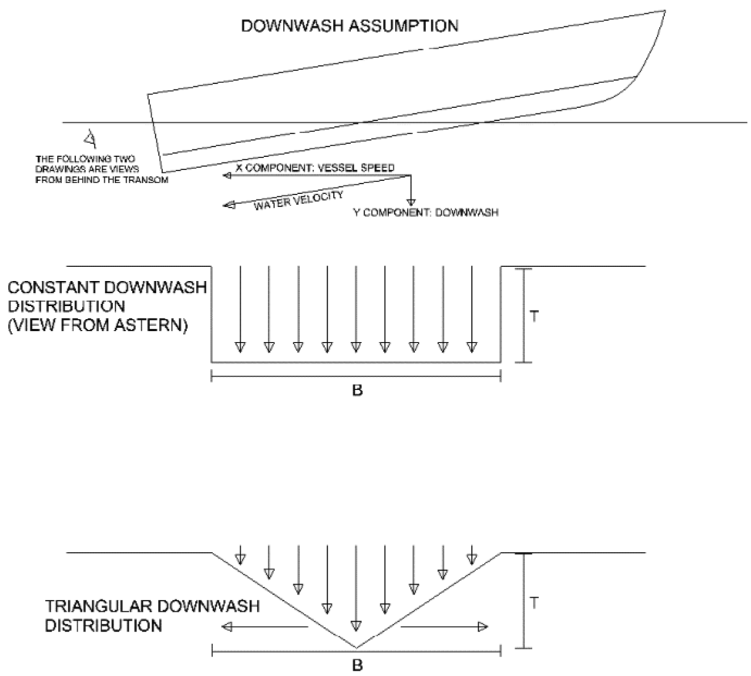

Figure 5. Downwash distribution regarding the shape of the bottom. Available from (Clayton, 2013).

It is important to notice that a flat bottom hull continuously produced higher waves than the V-shaped one, which was not of significance for work of Clayton, but will be in this thesis. This occurrence can also be related to downwash issue and its distribution along the beam (Fig. 5). The second explanation is that displacement is higher, resulting in movement of greater amount of water.

Other available materials focus mainly on catamaran design, which is logical considering much higher possibilities of multihull vessels to produce a low wake.

As many studies implicate, catamarans have the ability to use wave cancellation for their gain, and with doing so, reduce wake wash. Many different designs have been tested. One of most popular is a Weinblum arrangement of hulls where one of the hulls is in front of the other, to produce a canceling wave, Fig. 6, similar to how bulbous bow would on a monohull. These designs suffer from several issues. Knowing the nature of waves, it is easy to conclude that vessel like this can be optimized for only one speed. Further, asymmetrical design of a vessel produces a lot of unwanted stresses on the structure and heavily effects maneuvering.

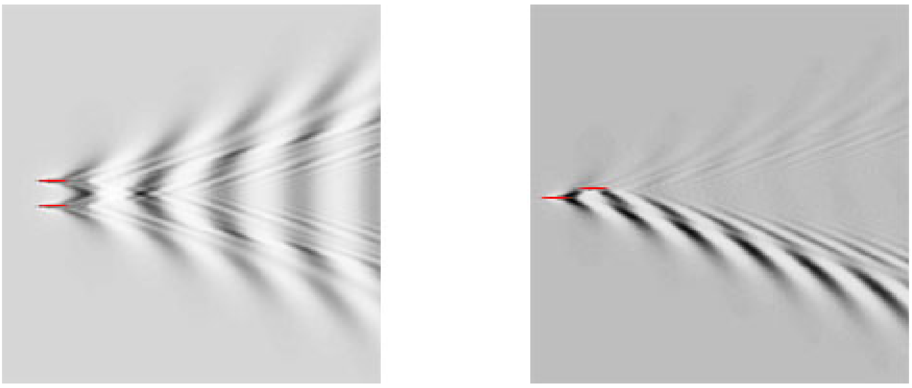

Figure 6. Wake Images created in Michlet. Available from http://www.graingerdesigns.net/the-lab/deltaform/wave-cancellation/ [Accessed 28 Nov 2016].

Another option is to use hulls that are individually asymmetrical, with a flat hull side on the outside (Fig. 7). This produces the effect opposite of racing catamaran that has a goal to reduce interaction between hulls. The result is inconvenient in a sense that people on board will fill more vibrations and noise, but on the other hand, wave reduction is almost unbelievable.

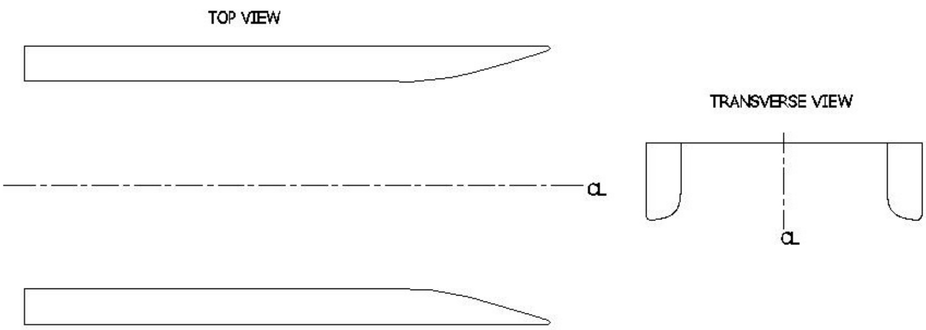

Figure 7. Asymmetrical catamaran design. Available from (Yaakob, 2009).

In the paper named Hull Form Considerations in the Design of Low Wake Wash Catamarans by (Stumbo, et al., 2006) dependence of wake wave height to Froude number is discussed in detail. This study reveals the difference between wake height hump and powering hump, by determining that wake hump happens just before the power one. The graph in Fig. 8 shows the position of wave bump related to Froude number.

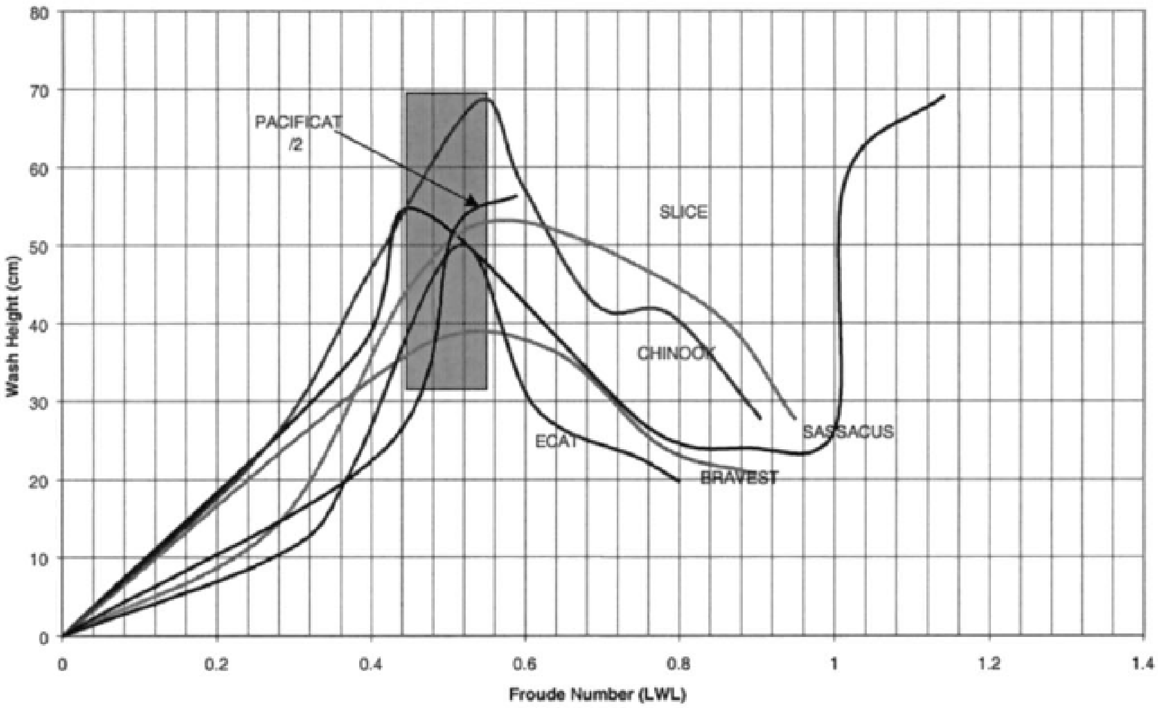

Figure 8. Wake hump vs. Froude number. Available from (Stumbo, et al., 2006).

2.5 Contemporary Developments in Patrol Boat Design

Patrol design is quite common, as said before in text. Over the years, many attempts are made to make the design more efficient and usable. Most of today’s modern designs are multihull vessels, due to reasons above.

Monohull designs, although becoming rarer are still being produced, mainly due to reliability and confidence people have related to them. In some specific cases, like the design considered in this thesis, service terms define the monohull as the leading choice (width of the vessel, available mooring space, need to sail in narrow waterways, etc.). Damen is international shipyard group that focuses a lot of its work to hull design. In recent years, their monohull design known by the name Sea Axe is getting a lot of attention. Other companies are following similar trends, making vessels more slender, and trying to achieve the best bow performance.

Several SWASH and SWATH designs are also in use. Their service has proved very reliable and very in line with first theoretical predictions. Due to the very low area of waterline, capabilities of these vessels are unrivaled. Problems come with some real-life expectances. These ships are much more complicated to navigate, so a number of trained pilots is still small. Further on, the cost of construction and the complexity of maintenance render them hazardous choice for continuous service. The author of this thesis firmly believes that these kind of vessels are the future, but sadly agrees that the future is still not here.

Fast comparison of three designs (Fig. 9) reveals main differences.

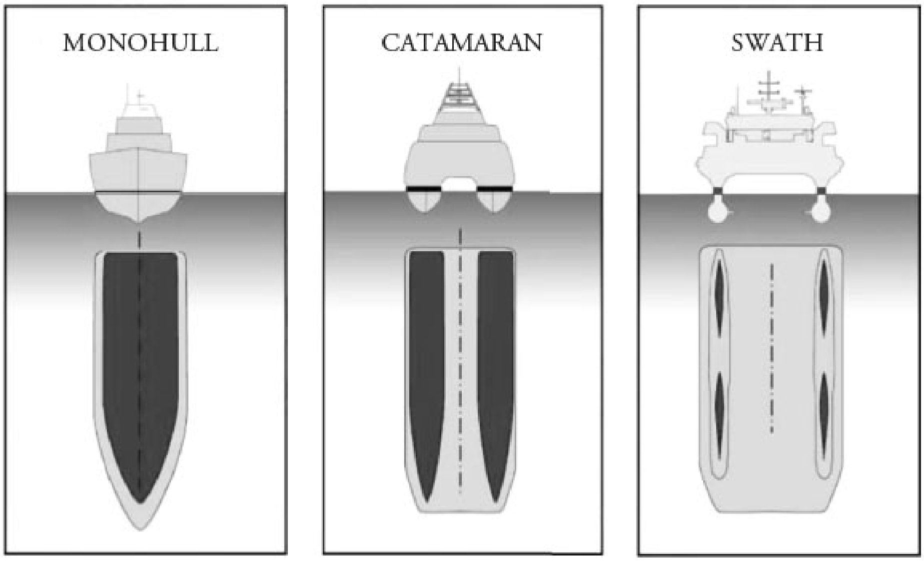

Figure 9. Comparison of different waterline areas. Available from http://www.shipjournal.co/index.php/sst/article/viewFile/120/370/3244 [Accessed 02 Dec 2016].

2.6 Section Summary

Although well explored, information related to hull design, in general, are kept secret. This comes from the need to make the best product, and to maintain that product inside an own shipyard. Analysis of modern hull shapes reveals important clues on how to obtain the best hull properties, both for seakeeping and creating an environmentally friendly vessel.

Control of wake is closely related to waterline length, through Froude number, but also to other hull characteristics that influence mainly diverging waves. Transom depth and shape will affect the formation of transverse waves.

3. PROPORTIONS AND PRELIMINARY POWERING

The design process started with a possible parent analysis, as many of design processes do. In this way, the designer is directly acquainted with common practice and possible problems to overcome (and how to overcome them) which provides for an easy escape from potential mistakes made in the past.

When in process of choosing designs to be analyzed, special care was taken to ensure similarity of chosen vessels to future design, as to have comparable results. All the constraints defined in Chapter Introduction are taken into account, and a list of 18 vessels is created.

Table 1. List of analyzed designs.

No	Name	Design	LOA	LWL	Beam	Draft	Disp.
			(m)	(m)	(m)	(m)	(kg)
1	Ares 42 FPB	Ares Shipyards	13,37		4,35	0,72	12140
2	Ares 42 Hector	Ares Shipyards	12,99	12,08	3,99	0,99	14000
3	Ares 55 Hector	Ares Shipyards	16,73		4,83	1,00	22000
4	MNI Patrol 15	Baglietto Navy	15,83	12,40	3,60	0,80	18000
5	13m Patrol boat	Camarc Design	13,60		4,20	0,90	15420
6	12m Patrol boat	Camarc Design	11,65	9,15	3,76	0,80	10510
7	14m Patrol boat	Camarc Design	14,00	12,20	4,00	1,00	16800
8	15m Patrol boat	Camarc Design	15,20	12,75	4,60	0,90	18880
9	15m Patrol boat	Camarc Design	15,10	13,10	4,75	1,13	24310
10	14m Fast SRB	Camarc Design	14,30	12,80	4,50	1,30	25100
11	13m SAR craft	Camarc Design	13,60		4,20	0,90	15420
12	14m Patrol boat	Camarc Design	14,00	12,20	4,00	1,00	16800
13	12m Patrol boat	Camarc Design	12,40	10,60	3,40	0,75	9490
14	Inshore patrol	Cheoy Lee	13,88		3,96	1,00	19000
15	13m Patrol boat	Holyhead Marine	13,20	11,50	4,60	0,90	12000
16	15m Patrol boat	Holyhead Marine	14,90	12,70	4,60	0,90	19900
17	16m Patrol boat	Holyhead Marine	16,50	14,50	5,30	1,30	24000
18	Baracuda	Safehaven Marine	13,70		4,20	1,15	14500

Aside from the data shown in Table 1 above, other information, like engine type, power, number of cabins, general arrangement, and tank capacity were also analyzed with a goal to produce a comprehensive overview of approximate characteristics of a future boat.

Making regression curves made the comparison much easier and created equations that could be used to calculate main dimensions for any given input. Graphs similar to ones shown in Fig. 10, under, are made for all the key components of the design.

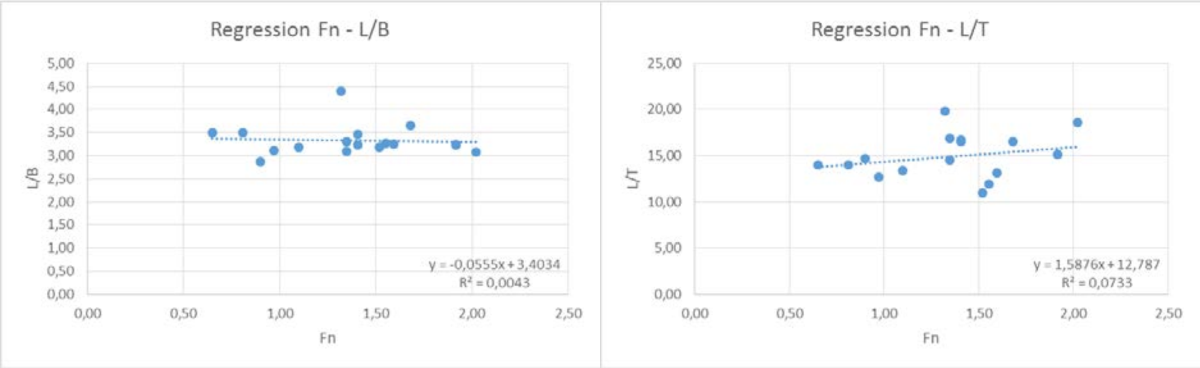

Figure 10. Regression curves defining principal dimensions and proportions.

Two graphs above show that the choice of vessels for analysis was right. The lines representing the ratio of L/B and L/T to Froude number are almost flat, which means that the characteristics of vessels are very close to each other. Calculations based on these curves provided width of beam on waterline BWL = 4,41 m and maximum draft Tmax = 1,1 m for desired length LWL = 15 m and maximum speed Vmax = 30 km/h.

Table 2. Main proportions as per regression equations

Chosen LWL	15,00	(m)
Chosen Speed	30,00	(km/h)
Chosen Speed	8,33	(m/s)
Fn	0,69	
L/B	3,40	
L/T	13,61	
BWL	**4,42**	**(m)**
Tmax	**1,10**	**(m)**
Estimated displacement	**16170**	**(kg)**

Analysis of this data also gave way to early powering predictions. Power required to thrust vessel of mentioned characteristics up to required speed of 30 km/h (8,35 m/s) is estimated to be in the range of 230 kW to 300kW.

4. HULL DESIGN

As could be concluded from the text up to now, hull design is the key design feature of this project. Derived from the wish to facilitate hull design for the requirements explained in previous sections, a short guide through aspects that affect the design will be presented at the end of this chapter.

4.1 Analysis of Existing Hull Designs

The array of hull designs available and used today is overwhelming. Luckily, a little bit of grouping makes the job of analyzing and comparing them much easier.

Even though every company has its design, and virtually countless of them exist, hulls of patrol boats in 15 m length range are usually one of three:

- Displacement hulls,
- Semi-displacement hulls,
- Planning hulls.

As the name says, displacement hulls are made to displace big quantities of water, and in turn provide a maximum of available space to the users. Even though space availability is one of the requirements in this part of research, these hulls cause severe disturbance of water surface and have high resistance values. In order to test these assumptions, displacement hull will be one of the possibilities.

Two of the following groups both have appealing characteristics. Semi-displacement hulls are characterized as a stable, well maneuvering and calm in rough conditions while planning hulls have lower resistance, ability to reach higher speeds and very low wave making at lower and mid-range of speed. Thus, several representative hulls from both of these families are modeled and will be compared.

After extensive analysis of possibilities and available designs, 5 of the most characteristic ones are chosen for preliminary tests. Main proportions, as acquired from sources are kept, and all vessels are scaled to same length and displacement. Figures 11-15 give line planes for each hull.

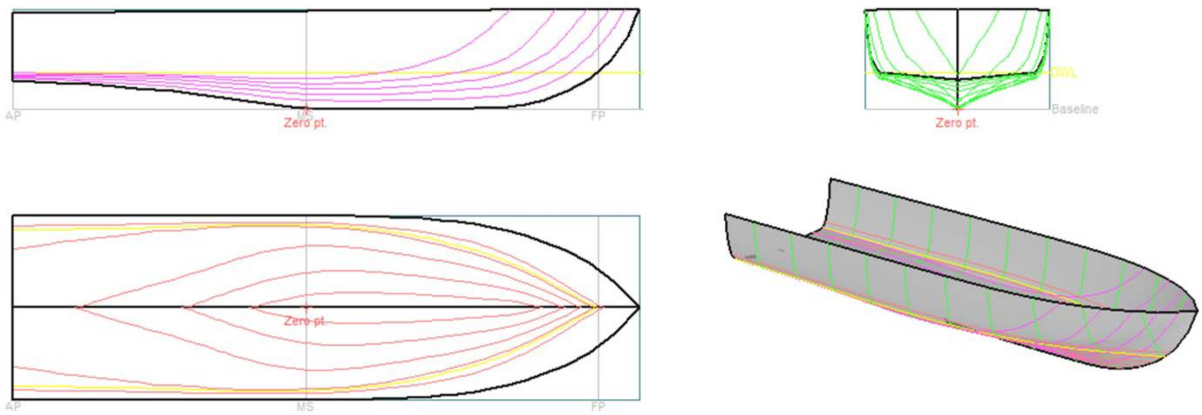

Figure 11. Round chine displacement hull. *Modell made as per original lines available on: http://trawlerschoolcharters.com/blog/wp-content/uploads/2013/09/boatlinessmall.jpg. [Accessed 18 July 2016].

As stated, hull above provides a lot of usable space due to very flat bottom in the mid and aft part of the boat. It also has the highest block coefficient of all the tested boats, so it is not a surprise to see that created waves are the highest within the group as demonstrated in Fig. 17.

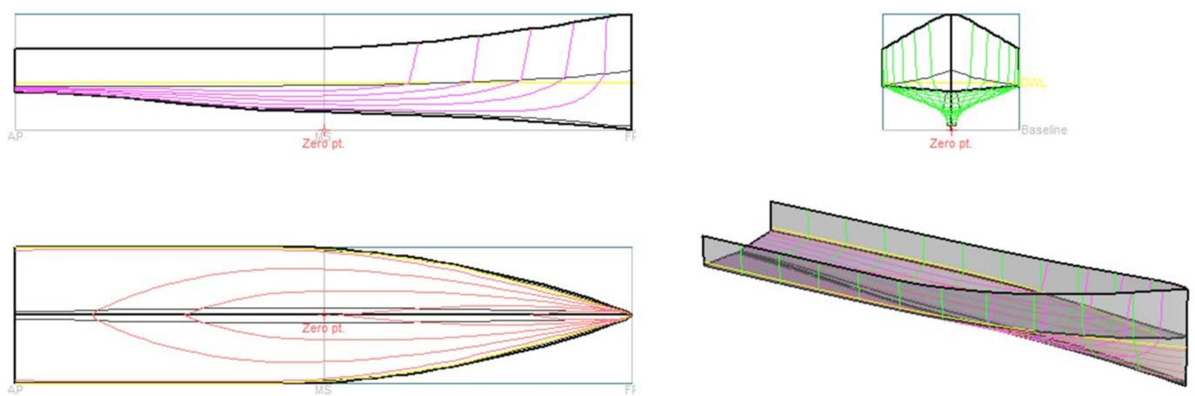

Figure 12. Semi-displacement Sea Axe® hull by Damen. *Modell made as per original lines available on http://www.boatdesign.net/forums/attachments/boat-design/42932d1273231420-axe-bow-concept-axe-bow.jpg. [Accessed 22 July 2016].

The hull modeled above is the product of joined work of Delft University and company Damen. It proved itself as a good choice in this case, just as it did for the newest series of ships produced by mentioned company. The slender design makes the angle of entry very low, but also renders a part of space unusable. The flaring in bow part makes it problematic to use in river environment where it can be damaged by contact with river bed.

To fix the last problem, following hull (Fig. 13) is made.

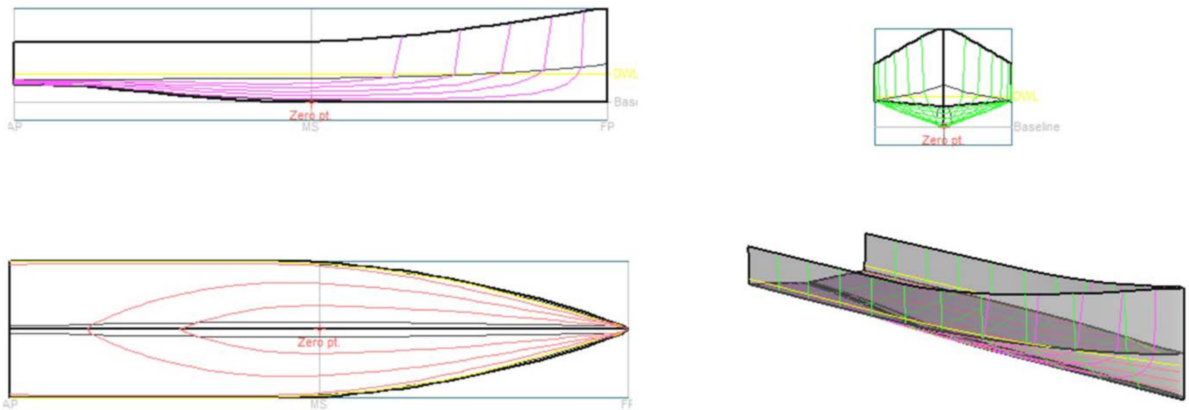

Figure 13. Semi-displacement Modified Sea Axe® hull by Damen.

Modified hull retained all the characteristics of the original with the exception that vertical bow flare is removed. In this way, the hull is much more user-friendly when navigating in water of limited depth.

Further, two hulls from planning family are considered. These two differ regarding chine design which means that later, double chine design, produces more lift at higher speeds. It also gives a possibility of controlling the trim by adjusting the longitudinal angle of the chine. Overall wave-making and resistance characteristic of these hulls (Fig. 17) are very similar.

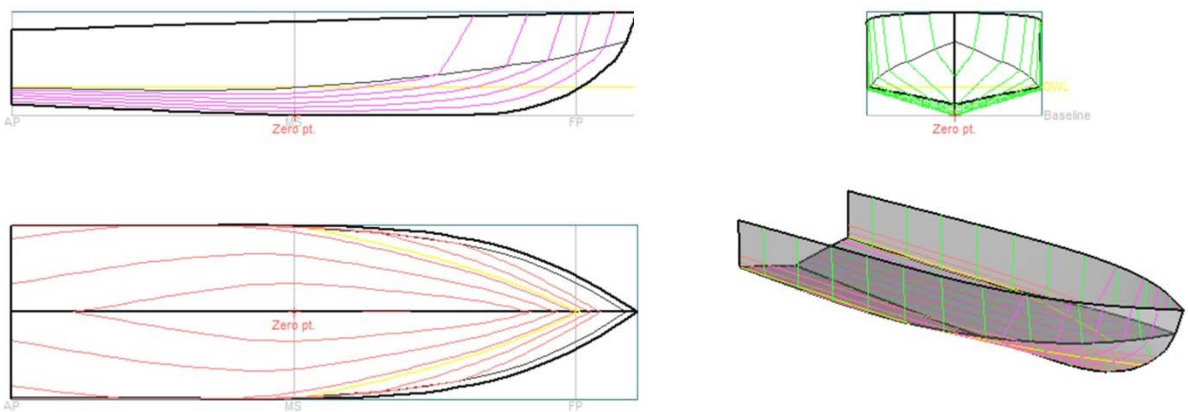

Figure 14. Planning single chine V hull. *Modell made as per original lines available on: http://www.huntdesigns.com/images/deepv-lines2.png [Accessed 17 July 2016].

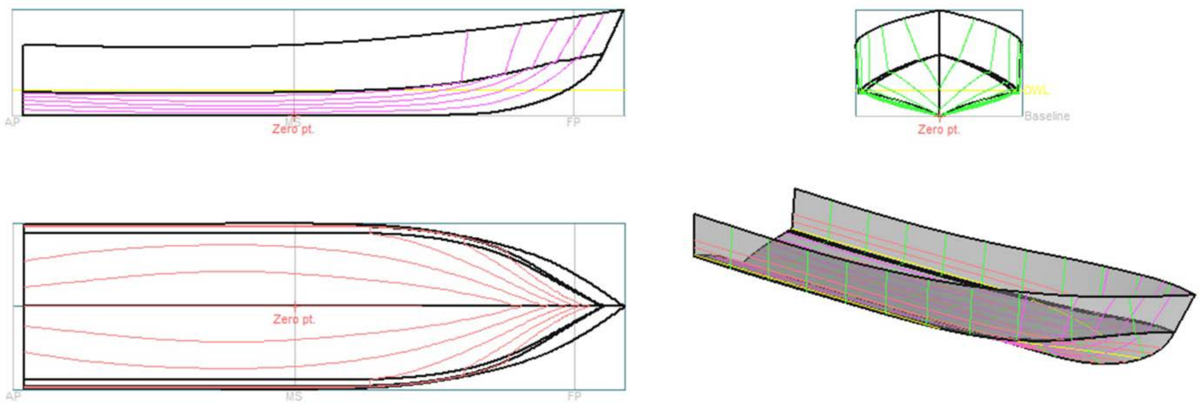

Figure 15. Planing double chine V hull. *Modell made as per original lines available on: http://www.skalamodelskibe.dk/forum/attachments/de26linesrev1.jpg [Accessed 17 July 2016].

Comparison of these models is done in software Maxsurf that calculates created wavefield based on slander ship calculation module that is a product of Neuman-Michell potential flow theory. It is important to notice that as such, these computations are being limited by all the assumptions of potential flow theory. Due to the non-viscous and linear nature of the approach results produced by Maxsurf are only suitable for preliminary tests that require fast solutions and serve as a comparison data to other models tested in the same manner. Since the attempt is to find the most suitable of these hulls, mentioned simulation is a perfect choice.

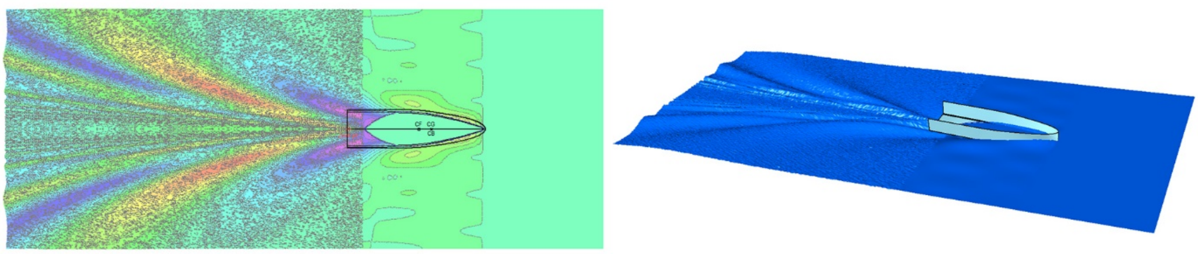

Figure 16. Waves as calculated by Maxsurf.

The software allows the defining of the domain size in which the vessel is navigating as well as the integration precision. Other factors influencing the waves are unavailable to the user, making the process very simple, but again, highly arbitrary regarding obtained results. Wave heights are given as a free surface position in regard to “zero point” and can be read graphically, and as a text file. An example of the graphical interpretation of results is given in Fig.16.

After obtaining all the results, they are compiled in Excel to determine the highest wave in the field. Simple graph (Fig. 17) summarizes all.

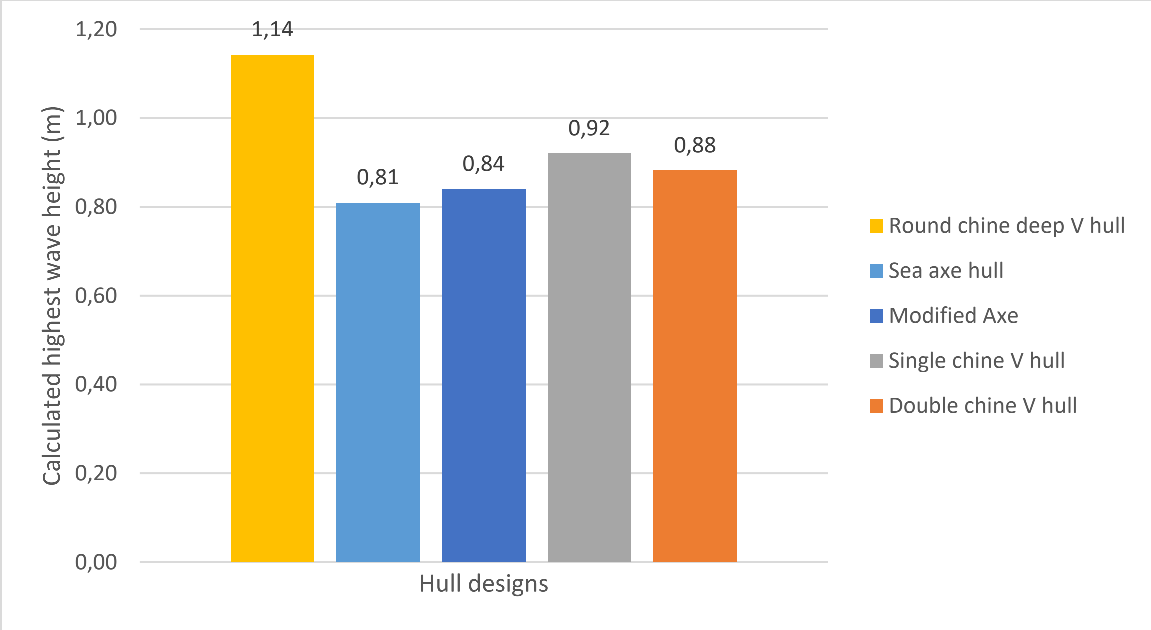

Figure 17. Comparison of wake waves.

4.2 Definition of First Hull

Modified Sea Axe hull and planning hulls tested show similar wake characteristics for the same displacement.

Planning hull has a wider beam, but a lower draft, whereas modified Sea Axe uses hull form that is close to slender boat L/B ratio to compensate for a slightly higher draft. Both hulls have positive and negative qualities that will be useful for future patrol boat

Planning hulls shallow draft is superior to another hull in river conditions, and while the difference in the draft is only 10 cm, it can prove valuable in day to day use. On the other hand, the bow shape of modified AXE ensures that bow stays underwater even in navigating through waves and in doing so minimizes overall vertical movement. Further on, maneuverability of planning hull will be superior to the Modified Axe, but extremely slender body results in 20% decrease in estimated power (as stated on www.damen.com), which again means less weight due to smaller propulsion components and tanks, etc.

Due to this array of possible comparisons, a new hull, combination of two mentioned above is made. It will ensure the mixture of all qualities needed to provide a sound basis for the patrol boat. The lines of the hull are shown in Figure 18 on the next page.

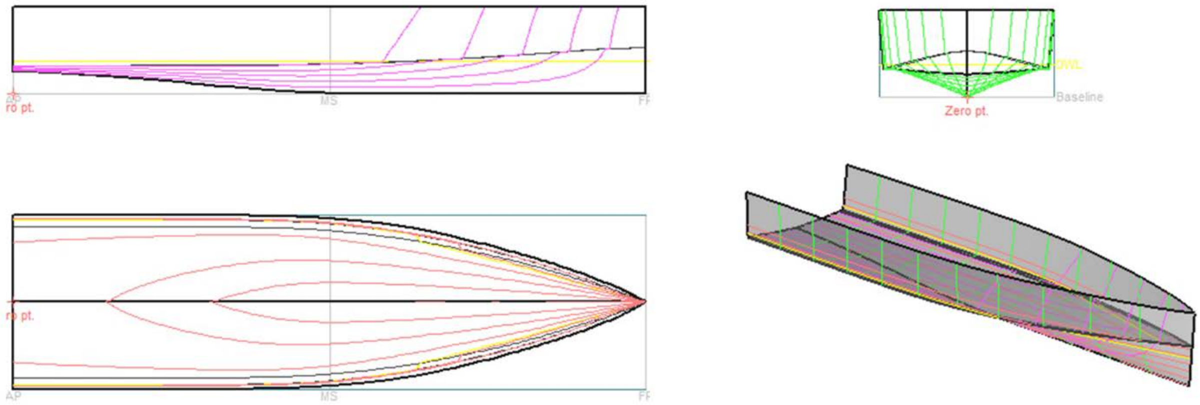

Figure 18. Hull for a patrol boat.

4.3 Hull Variation

To understand and simplify the problem of wake waves creation, this chapter will present a comparative analysis of 36 hull variations that has a goal to show the influence of different parameters to wave height in vessels wake.

To be able to compare the results clearly, all the vessels have the same displacement. Sometimes keeping the same displacement meant changing the draft, so all the wave heights are made non-dimensional by dividing them with the draft. This gives comparable results, dependable only on one parameter. The parameters that will be taken into account are:

- Draft/Beam ratio
- Speed
- Bottom deadrise angle
- Bow deadrise angle
- Chine longitudinal angle
- Half Angle of entrance
- Depth of transom
- Trim

Influence of Draft/Beam ratio to wake height

Testing of this parameter is done so a designer will make the right choice when in need of displaced weight.

It is easy to conclude that bigger draft or beam mean bigger waves. The problem is to assume which one of this two has a stronger influence on wave creation.

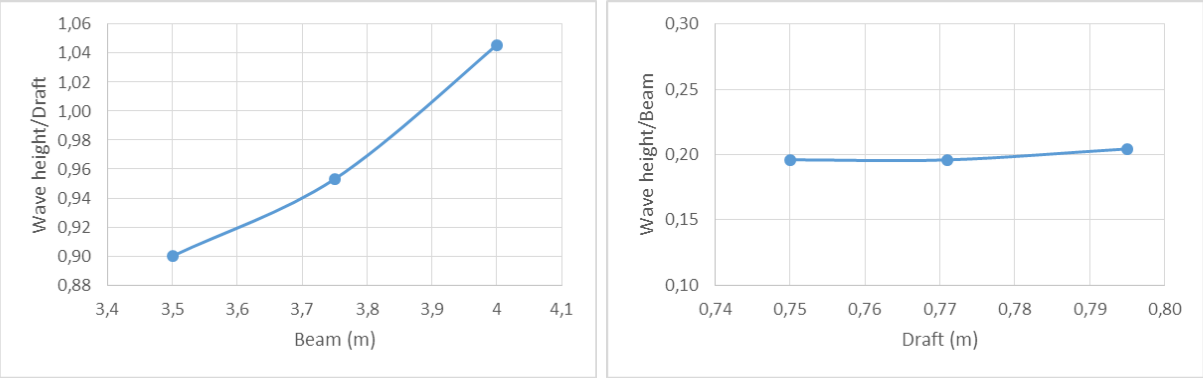

Figure 19. Wave height dependence on Beam and Draft independently.

Influence of draft exists but is very low compared to the effect of beam. Figure 20 shows that in order to keep low waves, the designer should increase draft and leave the beam as low as possible.

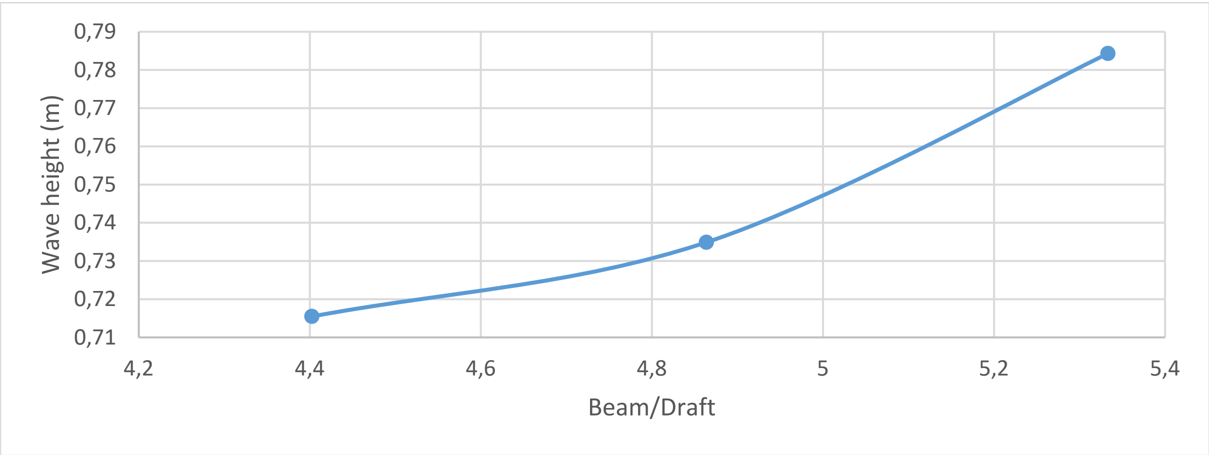

Figure 20. Wave height dependence on Beam/Draft ratio.

Influence of Speed to wake height

As described in one of the papers mentioned in section Hull Design in Function of Low Wake Generation, speed of the vessel has a substantial impact on wave generation. The development of waves behind the boat is not linear but is defined by humps, similar to the ones found when performing resistance tests. The goal of the design is to avoid these bumps to be at any of “defining speeds,” cruising or maximum speed in this case. Figure 21 shows the dependence of wave height to length Froude number.

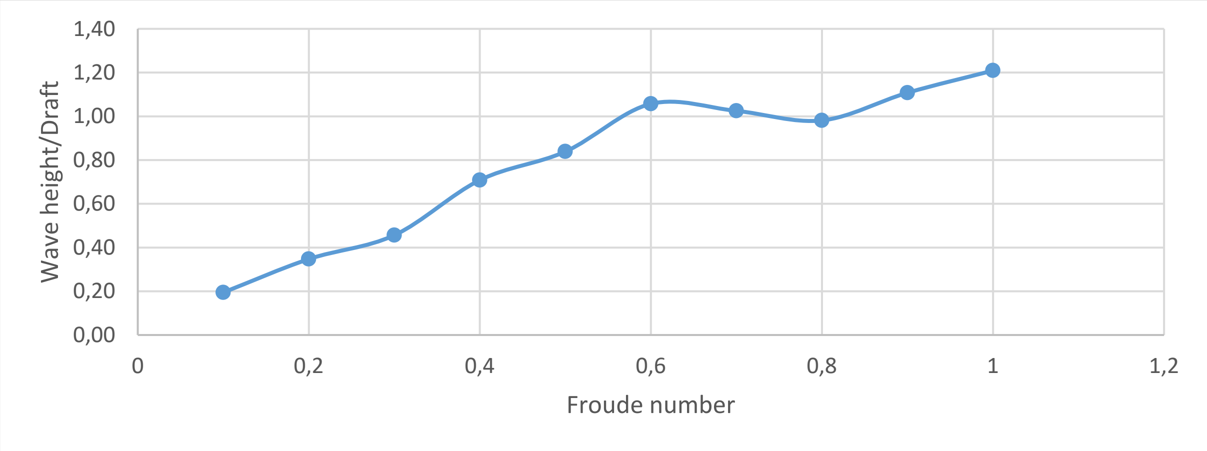

Figure 21. Wave height dependence on Froude number.

This shows that speed to avoid is at Fn=0,6. The maximum velocity for the vessel being designed is Fn=0,71 and cruise speed is at very low Fn=0,3, so the critical speeds are fully avoided.

Influence of Bottom deadrise angle to wake height

Bottom deadrise angle is not a parameter that can be universally measured. Every classification society or association of rules have their specific way to do it. In this case, bottom deadrise angle is considered as the angle formed by horizontal plane and line connecting lowest point of the keel and the outer edge of chine at midship. This angle is closely related to block coefficient so the influence on wake should be quite strong. Results show following:

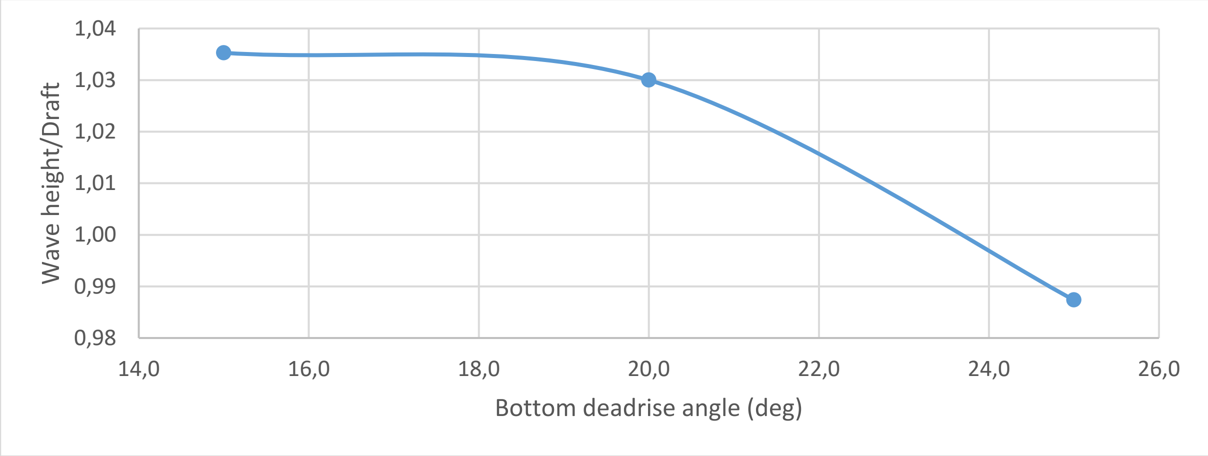

Figure 22. Wave height dependence on Bottom deadrise angle.

As stated before, higher Cb causes more water to be displaced, so it is logical that the waves are also higher. The steeper the angle, smaller the waves. This is one of the main reasons why catamarans are so good in not disturbing the water surface.

Influence of Bow deadrise angle to wake height

Bow deadrise is connected to half-angle of entrance, and it also has a strong influence on lifting forces in the fore part of the vessel. That is why vertical bow shows the best results in this regard.

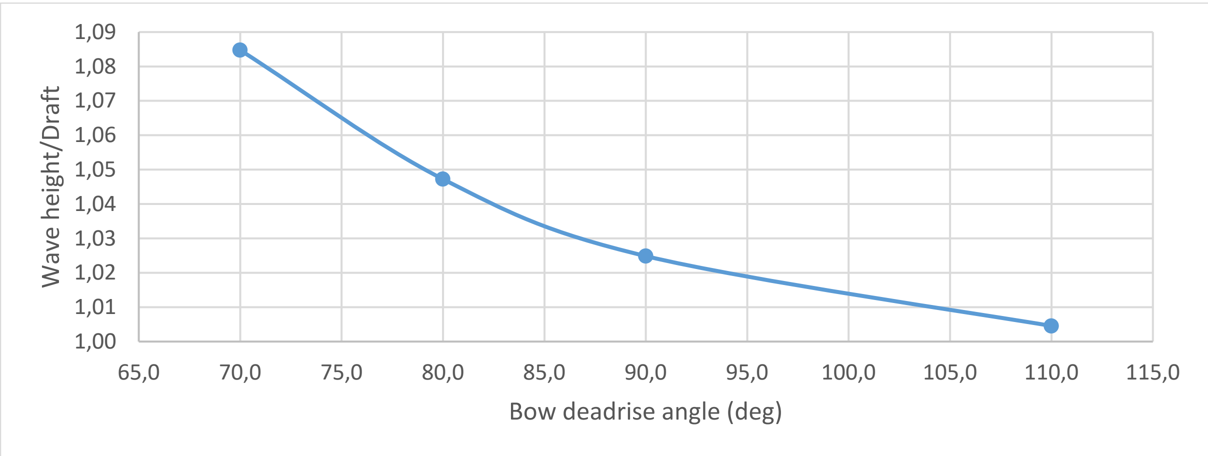

Figure 23. Wave height dependence on Bow deadrise angle.

It is shown in Figure 23 that angles of bow higher than 90 degrees would further lower the waves, but this solution would result in difficulties in maneuvering in small spaces, so this solution is abandoned.

Influence of Chine longitudinal angle to wake height

Chine longitudinal angle is not a standard definition in naval design, so Figure 24 will define the parameter.

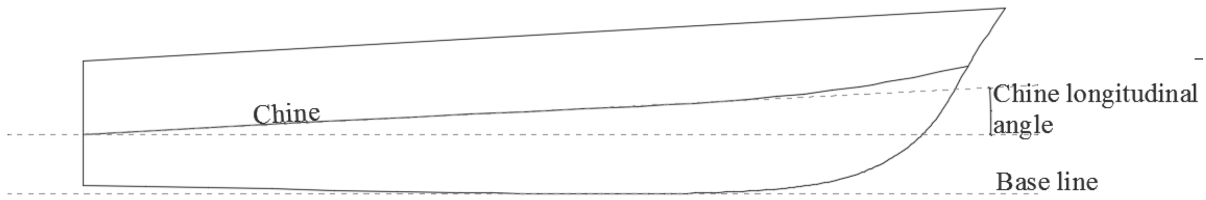

Figure 24. Definition of Chine longitudinal angle.

This angle has a double role in respect to wave generation. It makes the depth of transom higher which, as will be showed, reduces waves. It also directs water flow around the hull, and so controls the level of free surface disturbance. Figure 25 demonstrates how positive angle reduces the wave height.

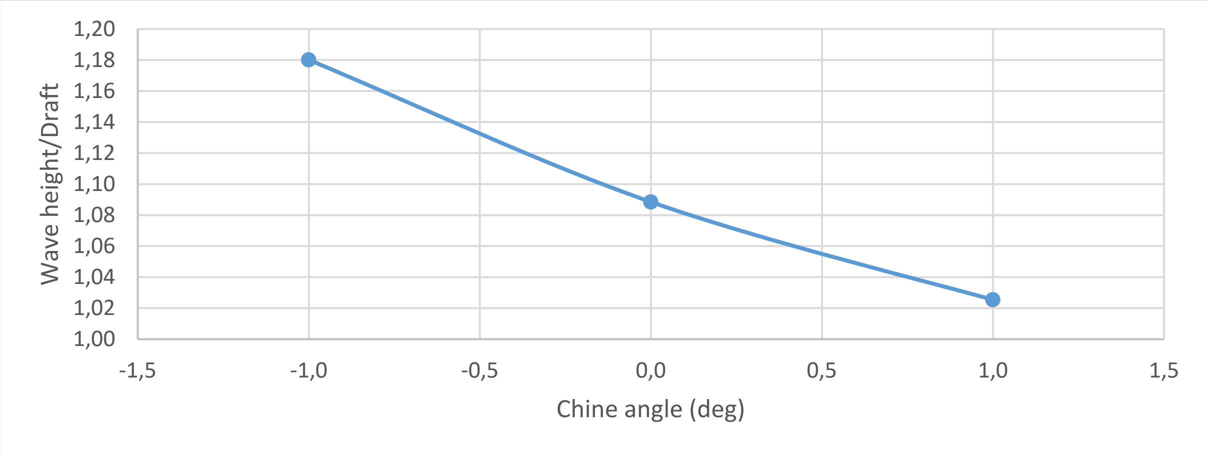

Figure 25. Wave height dependence on Chine longitudinal angle.

Influence of Half-angle of entrance to wake height

This is one of the parameters whose influence is very easily predictable. Finer angle means less disturbance and directly, lower wave height, which is proven by the graph in Figure26.

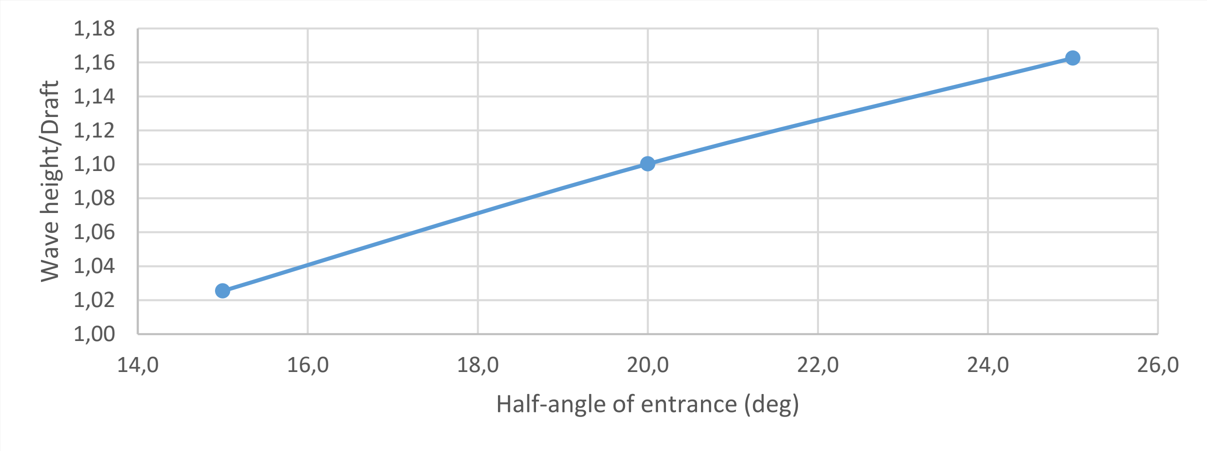

Figure 26. Wave height dependence on Half-angle of entrance.

Influence of Depth of transom to wake height

During previous discussion in this paper, it is defined that transom has a high bearing on the transversal waves. Although there are much more influencing parameters in this part of the hull, the strongest is the effect of depth of transom part. Simply explained, transom depth has a similar role like chine. The deeper it is submerged, less of the flow comes near the water surface. The influence is visualized in Figure 27 under. It is beneficial to know that depth of H=0,75 m is equal to the draft of the vessel.

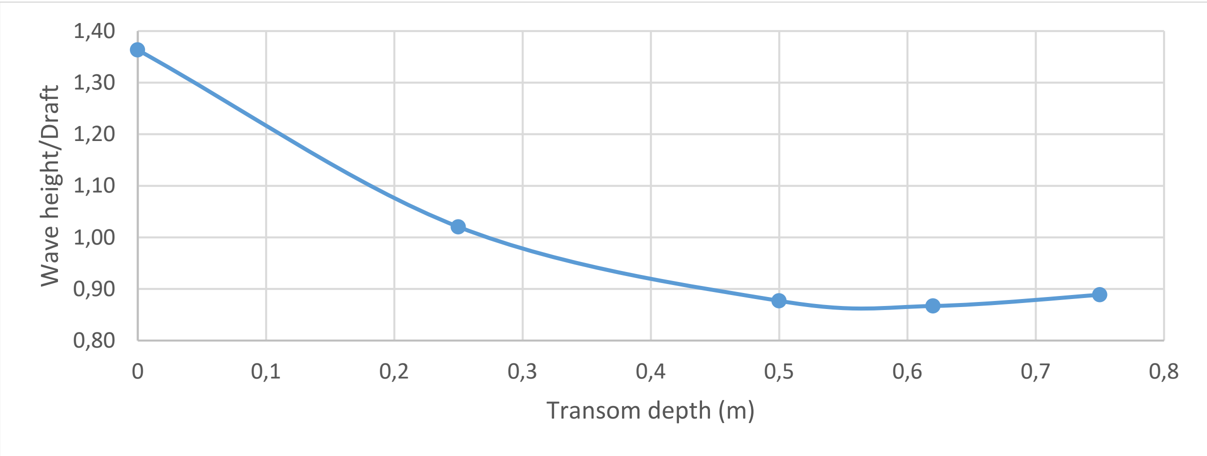

Figure 27. Wave height dependence on Transom depth.

It is evident that waves become smaller very fast when transom finishes close to the surface, but the deeper transom is, influence on wave generation reduces. Along with the trim that is discussed in next section, this is the highest impact compared to other parameters.

Influence of Trim to wake height

Influence of trim combines several previously discussed parameters. Due to excessive trimming, the angle of entrance is compromised, as well as the angle bow deadrise angle. Those reasons explain increased waves in case of positive trim (by bow). Trim by stern, however, brings problems as negative chine angle or shallow position of the transom. That is why every trim brings higher waves as shown in Figure 28. Due to the lower influence of first two parameters (in the case of positive trim), wave increase is noticeably smaller.

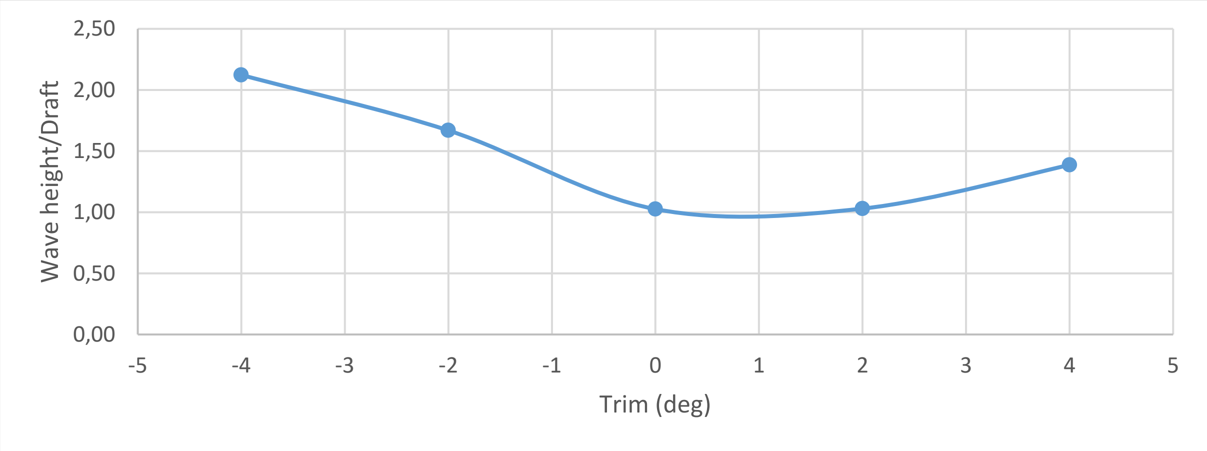

Figure 28. Wave height dependence on Trim angle.

4.4 Section Summary and Final Hull Definition

Previous text gives a „quick how to" on the subject of low wake hull design. Important is to know that all the parameters defined afore and the established influence of those parameters are also applicable for the problem of lowering vessel resistance, due to previously discussed wave resistance component.

Before the definition of final hull shape, it is also beneficial to say that the condition of small wake waves height was not the only one taken into account and that the hull is the product of a combination of all set requirements. This means that, although different hull shape in some areas could have further reduced the height of wake waves, that particular hull shape may not have been chosen in order not to compromise other premises (e.g. low draft requirement or spatial needs).

Following figure (Fig. 29) shows the hull of hydrostatic characteristics as given in Table 3.

Table 3. Hydrostatics of chosen hull

Measurement	Value	Units
Displacement	13,18	t
Volume (displaced)	13,180	m^3
Draft Amidships	0,750	m
Immersed depth	0,750	m
WL Length	14,400	m
Beam max extents on WL	3,800	m
Wetted Area	48,283	m^2
Max sect. area	1,374	m^2
Waterpl. Area	41,557	m^2
Prismatic coeff. (Cp)	0,666	
Block coeff. (Cb)	0,320	
Max Sect. area coeff. (Cm)	0,518	
Waterpl. area coeff. (Cwp)	0,758	
LCB length	6,600	from aft perp. (+ve fwd) m
LCF length	5,696	from aft perp. (+ve fwd) m
LCB %	45,832	from aft perp. (+ve fwd) % Lwl
LCF %	39,560	from aft perp. (+ve fwd) % Lwl
VCB	0,537	m
KB	0,537	m
BMt	3,116	m
BML	38,993	m
GMt corrected	3,653	m
GML	39,530	m
KMt	3,653	m
KML	39,530	m
Immersion (TPc)	0,416	tonne/cm
MTc	0,362	tonne.m
RM at 1deg = GMt.Disp.sin(1)	0,840	tonne.m
Length:Beam ratio	3,780	
Beam:Draft ratio	5,080	
Length:Vol^0.333 ratio	6,096	

As is visible in Figure 29 and from body plan drawing, the lines defining the hull are as flat as possible. This means that construction will be easy in a sense that almost all of the body is curved in one direction.

The upper part of the bow is flared to reduce bow wave and possibility of spray on the deck. Bow is rounded at the point of entrance to ensure good hydrodynamics and easier manufacturing.

Moulded beam is 4,0 meters and provides enough space for all on-deck equipment, but the beam on the waterline is 3,8 meters to increase slenderness.

The chine on the hull is designed in such a way that it is at a positive longitudinal angle. This serves a purpose of reducing the waves, and it ensures lowered trim in conditions of higher speeds. The chine is reduced to zero in forepart not to create lift forces on the bow.
The depth of transom is at the maximum allowed by the draft restrictions set by the client and needs of the propulsion system.

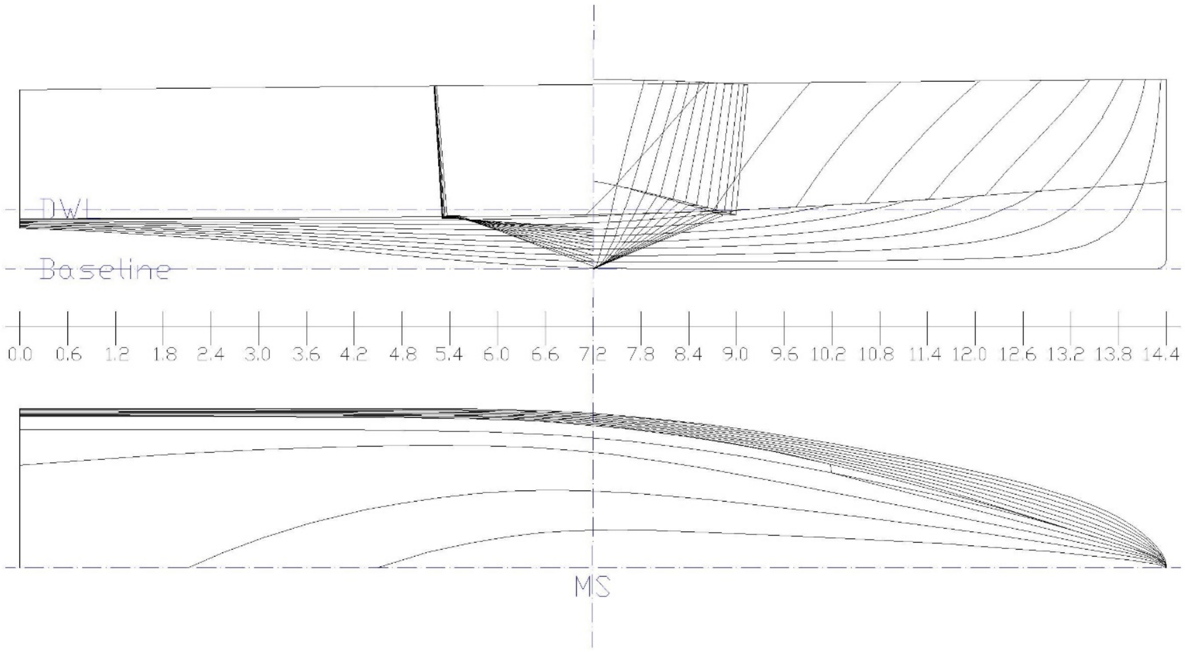

Figure 29. Lines plan of the chosen hull.

Above defined hull shape is also tested to determine resistance and wave heights and results obtained from 2 sources, potential flow solver and CFD code based on Navier–Stokes equations are in good accordance. Figure 30 and 31 give a brief overview of results of CFD simulation, while Figure 32 gives a comparative summary of all results provided by the Potential flow solver.

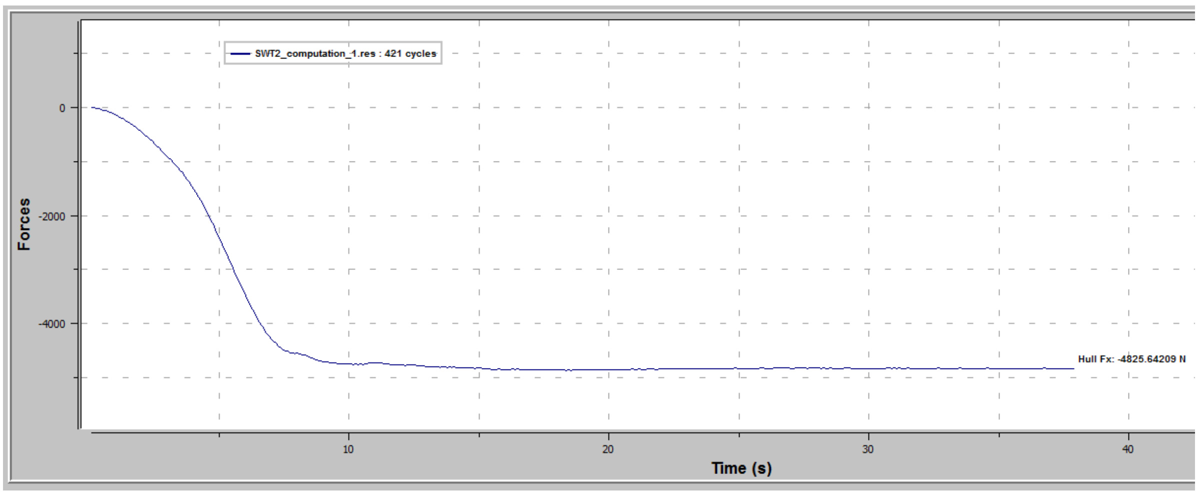

Figure 30. Fx - Resistance force on the hull.

Maximum force on half-hull at speed of 8,35 km/h which corresponds to maximal speed requested by the client is 4825 N, which provides a total force on the hull equal to 9650 N. This result will be used as a guide for powering but will be increased by safety factor due to two main factors:

- CFD code provides underestimated result in the case of coarser mesh, which is the case here.
- To speed up the testing, motions of the hull are not taken into account in this test.

Further on, Figure 31 shows calculated wake field behind a vessel moving at maximum velocity.

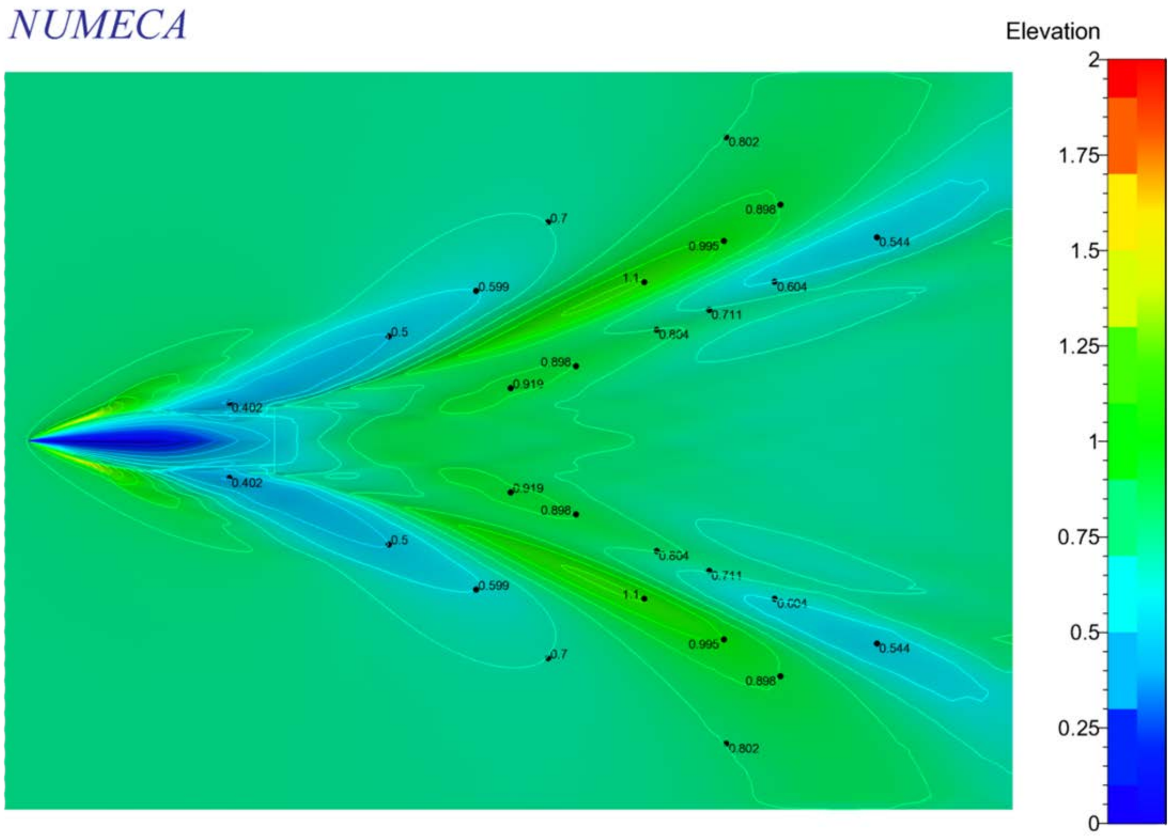

Figure 31. Wake wave height model.

Isolines on the chart above are 0,05 m apart and give a good idea about wake field. It can be read that maximum wave in the field has a height of 0,698 meters. To put this in perspective, a comparison to previous models will be made.

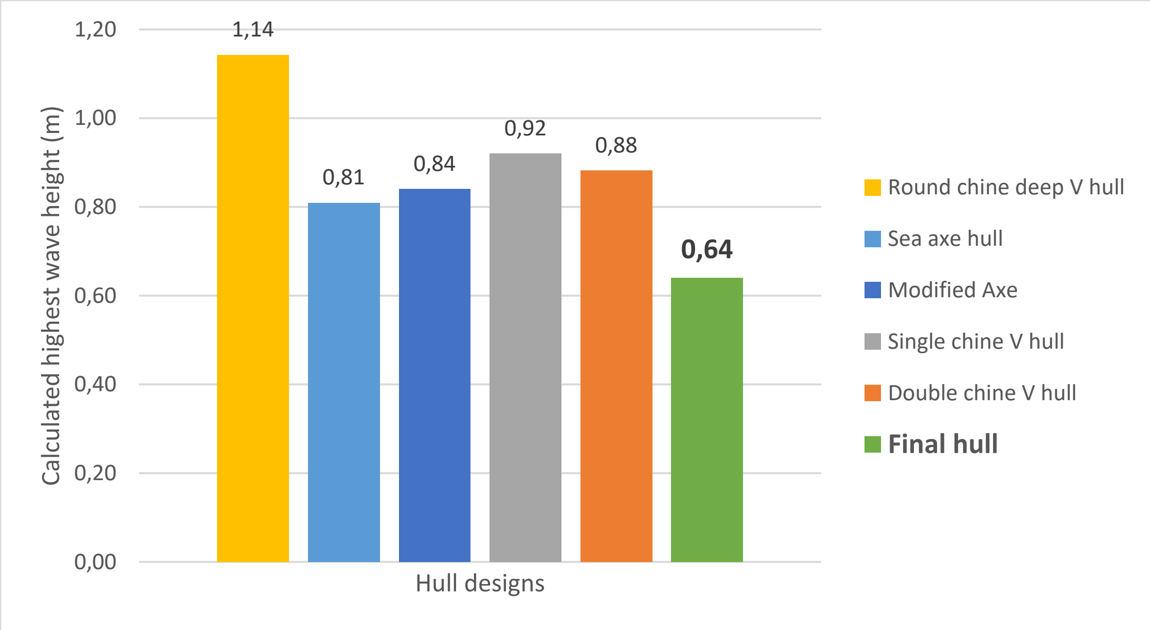

Figure 32. Comparison of wave height results between non-refined and refined hulls.

All the results on the graph above come from the same solver, Potential-flow based MAXSURF, using same domain attributes.

At the beginning, it is important to notice the similarity of wave height produced by CFD solver and result from the Potential flow. The difference is less than 8%.

Further on, it is more than obvious from Figure 32 demonstrates that applying previously defined changes gave positive results. The reduction of waves compared to best-ranked hull from the first group is 14%, and more than 35% compared to the worst hull tested.

5. GENERAL ARRANGEMENT

**NOTE: Technical drawings for close inspection and analysis are given in section APPENDICES. Drawings shown in present section are scaled down for easier reading experience.*

So far, data has been gathered from parent analysis, main space requirements estimated and hull shape has been defined. Following part will provide insight into the spatial organization, a division of functions and design choices.

Absolute paramount in the design process is the functionality. Being a working boat, luxury and comfort are not what the interior should strive for, but sometimes, a clean function is the hardest to achieve.

5.1 Space Zoning

Zoning is the first of the design steps. It needs to be done very early in the process so that mixing of incompatible functions is avoided.

Analysis of duties of patrol boat showed the necessity for three separate zones. Figure 33 gives a visual of spatial disposition for:

- Assignment task zone – Blue color
- Off-duty zone – Yellow color
- Mechanical zone. – Red color

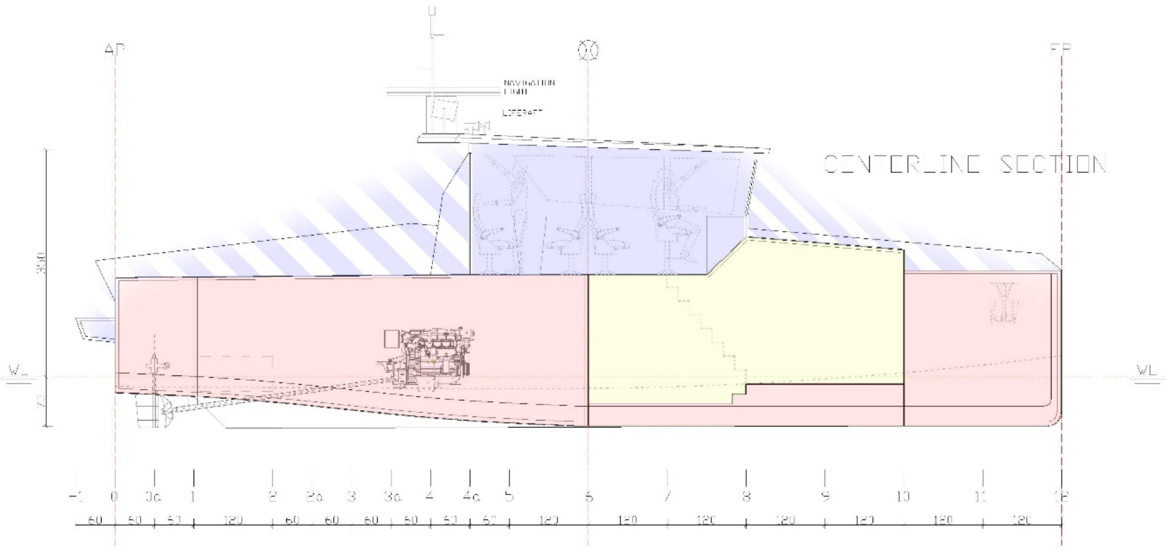

Figure 33. Spatial organization.

Zones are divided so that overlays are minimal, and are also tightly grouped to avoid long corridors and waste of available area. Further, areas prone to be occupied during most of the time are placed in midship, providing minimal motions in all conditions. Following zoning, main deck plans are made with more details.

5.2 Lower Deck

Lower deck contains two out of three presented space types. Division between these is engine room bulkhead at midship and collision bulkhead at 2,4 meters from forepeak. Such positioning places living space in the safest area on board. Figure 34 helps to visualize this concept.

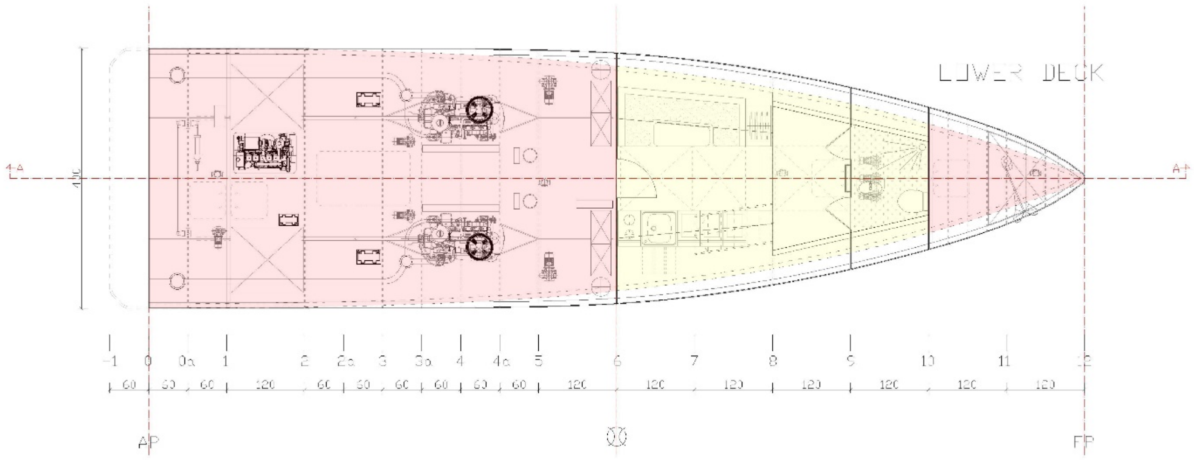

Figure 34. Lower deck arrangement.

Colouring scheme from the previous section is kept here to accentuate clear functional divisions further.

Machine spaces, in red color, contain engine and steering gear room with all equipment necessary. Due to high usage profile of boat, particular attention is given to size and organization of engine room, to enable swift maintenance. The engine room is accessible from crew space, through bulkhead door, or directly from deck via hatches. Some of the tanks are positioned under crew area, here shown in yellow, but Figure 33 defined that space as machine space. Forepart of machine space is reserved for anchoring and mooring equipment as well as for storage of deck utilities.

Crew area on lower deck contains:

- Toilet
- Shower
- Storage space for uniforms and personal belongings
- Secondary storage for additional weapons and ammunition
- Transformable dining area with sofa available in single bed configuration
- Kitchenette.

Crew space has direct access to sunlight and natural ventilation. In order to provide necessary height, it is divided into two parts by a denivelation of 30 cm. This is done to avoid changes in height of floor in main deck cabin that is the primary center of operations on board. As such, ease of movement through it is necessary.

5.3 Main Deck

The main deck provides space necessary for officers to perform their duties. It is comprised of closed and opened area where all the different tasks may be conducted. Aft and forward decks are designed to have minimum obstacles. In the far aft, sitting bench with storage space under hides stern anchor and some of the equipment.

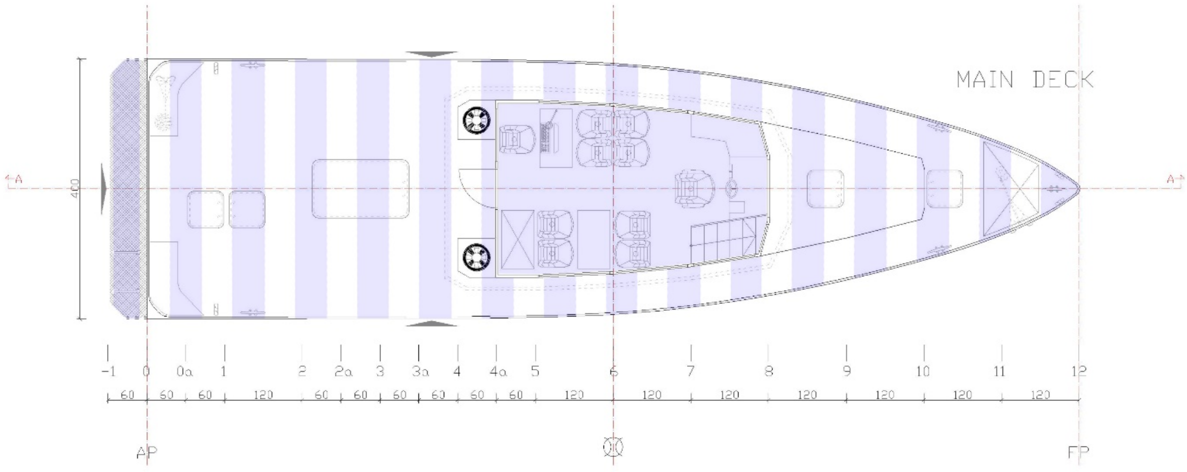

Figure 35. Main deck arrangement.

Figure 35 also shows three ways to access the vessel, on port and starboard side and in the aft. Multiple possibilities of boarding and disembarking make it easier for the crew to plan necessary actions. Hatches on deck give direct access to steering gear room, engine room, crew area on lower deck and forepeak storage.

Enclosed cabin is the heart of this boat. It can seat up to 9 persons, not including the pilot. Helm is designed so that boat can be operated by a single man. The position of the pilot chair provides the pilot with an almost unobstructed view in all directions thanks to big windows. Storage space on the starboard side is intended as primary tactical storage. Port side is equipped with an independent computer, directly connected to the police database, enabling a fast check of necessary data.

5.4 Exterior

Although the shape of this boat is mainly governed by earlier mentioned premise that form follows function, it will not be entirely left adrift. The Inland Police of Belgium already have a distinctive pattern that makes the vessels under its command recognizable. This design will be used for the present project, but adapted to the new shape and modernized.

All vessels under the command of the Directorate of Maritime and River Police are painted in the following scheme: blue hull, white superstructure, stripping on the biggest continuous white surface. An example is SPN 15 shown in Figure 36.

Figure 36. Paint scheme of SPN vessels.

The outline of the vessel is another way to define the nature of it. This boat, being that is used by authorities needs to have a sleek and aggressive design. This was done by applying straight lines and bold cutting angles, as shown in Figure 37.

The combination of lines and colors proved to be very effective, so the following image gives the artistic impression of the future vessel.

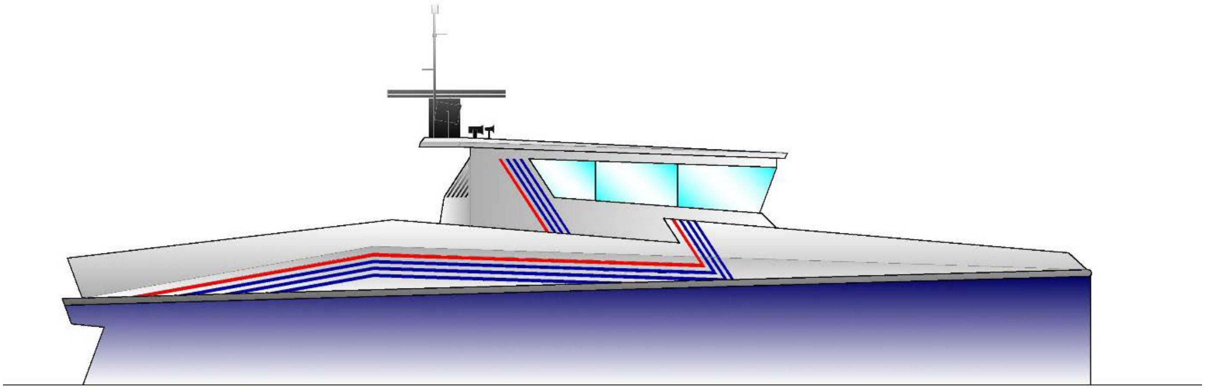

Figure 37. Exterior look of the new boat.

6. PROPELLER DESIGN AND ENGINE DEFINITION

With the resistance known, it is possible to design the propulsion system. This part is also important for the upcoming weight estimation that makes no sense with engine or propeller characteristics unknown.

It has been decided to incorporate twin-screw propellers to the boat. Having two propellers with their respective rudders will help when manouvering at low speeds or in constrained areas.

6.1 Propeller Dimensioning

In this section, the propellers will be designed taking into account the following considerations:

- Hull form constraints: There should be a gap between the top part of the propeller and the bottom of the ship
- Resistance: The propeller should be able to provide enough thrust to overcome the hull resistance
- Manufacturing/production: The design should be realistic; therefore, commercial catalogs will be compared with the design

The procedure to design the propellers is:

- To define diameter based on hull constraints
- To find the minimum E.A.R. regarding cavitation (Keller's formula)
- To employ a Wageningen B-series chart to find the most efficient design
- To obtain the final parameters of the propeller

The diameter will be the maximum possible while respecting the necessary gaps or spaces between propeller and rudder or the bottom of the hull. These distances are specified in different textbooks as well as by the classification societies; the following graph represents the values considered in this analysis:

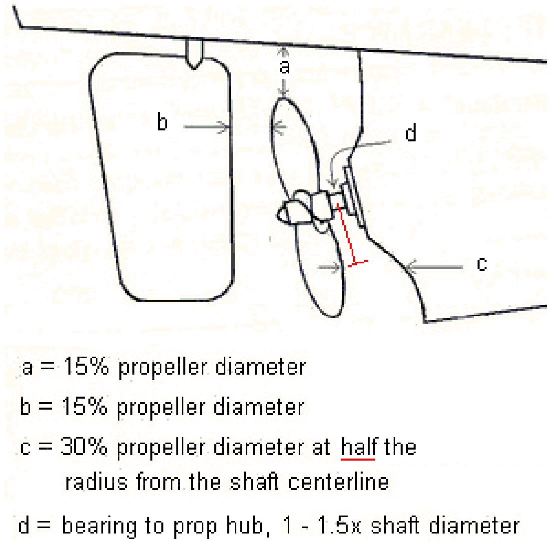

Figure 38. Requirements of propeller gaps.

Spatial allowance defines propeller of D = 0,5 m.

Further, required Ae/Ao ratio is calculated which is for a three bladed propeller since those are, according to the manufacturer, considered the « industry standard» for medium speed boat inboard cruisers and it is designed for applications where smoothness and performance are essential.

Ae/Ao ratio for propeller of D = 0,5 m and Z = 3, operating in fresh water is

Ae/Ao = E.A.R. = 0,53

In order to use Kj-Kq-J diagram, Kt/J^2 is calculated, and optimum curve of the propeller is drawn on Wageningen B 3.55 diagram.

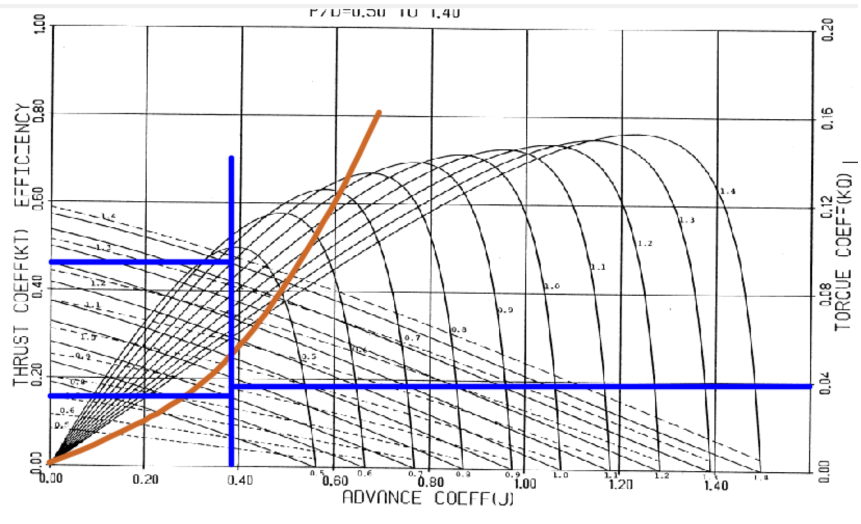

Figure 39. Kj-Kq-J diagram of Wageningen B 3.55 series propeller.

This diagram provided the set of needed values to finalize the propeller calculations.

- J = 0,38
- Kt = 0,25
- Kq = 0,036
- P/D = 0,9
- η = 0,50

Data above gave way to calculate necessary RPM for cruising speed. The obtained value is

N = 990 rpm for Q(thrust) = 0,308kN.m and Pd(delivered power) = 32kW

Since the overall efficiency of 0,5 is in good accordance to previously assumed one, and is well suited for this type of vessels, the final chosen propeller is MAUCOUR HYDRAPOISE 3.55 (reference HJD 200) with diameter of D = 508 mm, shown in Figure 40

HYDRAPOISE 3.55

The HYDRAPOISE 3.55 is considered the « industry standard» for medium speed boat inboard cruisers and it is designed for applications where smoothness and performance are essential. With a disc area ratio of 55%, it can be used on displacement craft when the power is considered too high for the HYDRAPOISE 3.45.

The HYDRAPOISE 3.55 can be manufactured from either high tensile manganese bronze or nickel aluminium bronze.

DIAMETER		PITCH (Inch)		SHAFT Ø	Ref.
Inch	mm	MIN	MAX	MAX mm	
12	305	8	12	25	HJD120
13	330	9	13	30	HJD130
14	356	10	14	30	HJD140
15	381	10	15	30	HJD150
16	406	11	16	30	HJD160
17	432	12	17	30	HJD170
18	457	12	18	40	HJD180
19	483	13	19	40	HJD190
20	508	14	20	40	HJD200
21	533	15	21	45	HJD210
22	559	15	22	45	HJD220
23	584	16	23	50	HJD230
24	610	17	24	50	HJD240

Figure 40. Chosen propeller by Maucour.

6.2 Engine Definition

Once the propeller has been designed, the next step is to select a suitable engine. The required power of the engine will be larger than assumed due to the losses:

- Shaft efficiency: It is considered as η_{sh}=0.95
- Gearbox: As it will be shown later on, a gearbox is needed to match the difference between the rotational speed of the propeller and the engine. The friction in the gearbox produces some losses. The efficiency has been considered as η_{gb}=0.92

Furthermore, when the boat sails on the river, the conditions are worse than in still water condition and typically a margin is included. It has been decided to consider a 5% river-margin:

$$P\text{B}=65*1.02*1.05*1.05=746.65(1-0.02)=78\text{kW (per engine)}$$

The engine chosen for the vessel is VOLVO PENTA D5A TA Diesel inboard. It has following characteristics:

- 4 cylinder, 4 stroke
- 4,76 L of displacement
- Weight with gearbox 570 kg
- Power of 96kW @ 2300 rpm

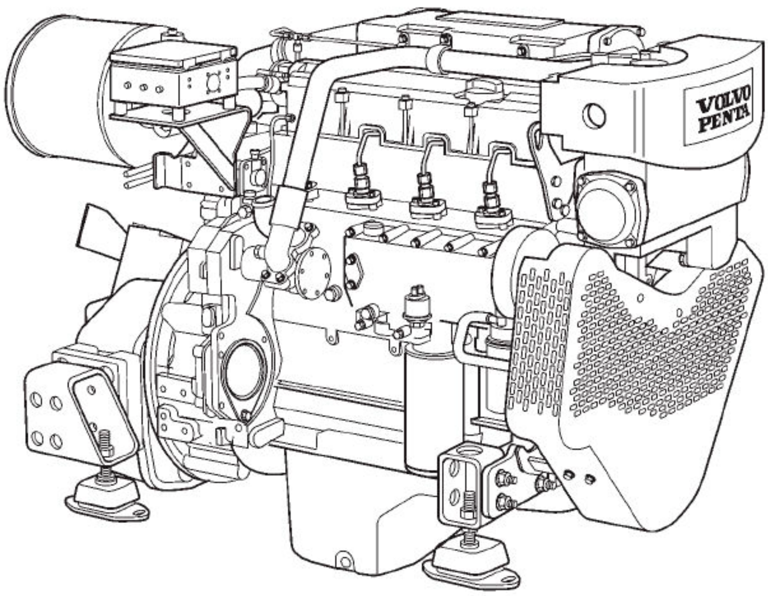

Figure 41. Volvo Penta D5A TA.

This configuration is chosen in order to provide the required span of rpm to propellers. As defined by VOLVO, working range of the engine is 1000 rpm to 2300 rpm. Due to the difference in working range of propeller and engine, a ZF 45A gearbox with a ratio of 1,256 is chosen to provide reduced range of 660 rpm to 1520 rpm.

Previous section allows the creation of propeller curve that shows the propeller RPM range versus delivered power. That range is then compared to engine power output in Figure 42.

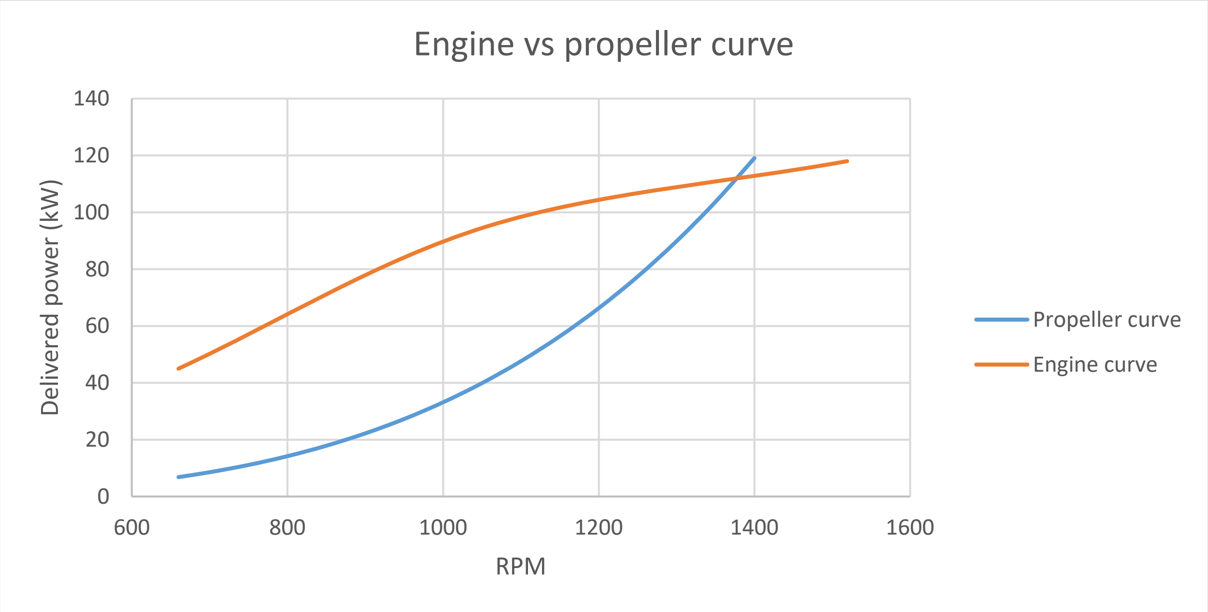

Figure 42. Comparison of engine and propeller working domain.

It is evident that there is a big amount of extra available power throughout the RPM spectrum. This difference exists due to the high difference of cruising and maximum speed power needs in this vessel.

It is true that in this case, maximum efficiency of the engine is not achieved since it works on much less than 80% of load, but, on a good side, it is clear that performance in sight of quick accelerations and response time will be exceptional.

7. STRUCTURE AND SCANTLING

Considering all the needs of the boat at hand, aluminum was a clear choice for building material. When compared to steel, aluminum structures are considerably lighter, and since weight negatively affects all the aspects of this build, steel was not a viable option. FRP hulls are even lighter than aluminum ones, but, this boat may be subject to rough treatment due to its function, and as everyone knows, FRP does not cope well with accidents.

Rules used for calculation of structural members are provided by Bureau Veritas (BV). The calculated properties obtained for each member will be provided in following sections, and those will be compared to properties chosen for the build. The differences between these two exist to satisfy needs other than mere structural soundness of a hull (production requirements and so on).

7.1 Rules Definition

As stated by BV, Section B–Hull Design and Construction of Rules for Inland Navigation Vessels - November 2014 edition (entry into force 1 February 2015) can be applied only to „vessels whose hull is of welded steel construction." However, they also state that „Vessels with rule length exceeding 135 m, vessels whose hull materials are different than those mentioned in [1.1.1] (steel hulls) and [1.1.2] (steel hulls with parts of hull in aluminium) vessels with novel features or unusual hull design are to be individually considered by the Society, on the basis of the principles and criteria adopted in the Rules."

This means that the rules provided can be adapted to use for hulls built of aluminum if right material properties and factors are taken into account. Ergo mentioned set of standards will be utilized in order to provide elements scantling for this project.

The specificity of the set of rules named - Inland Navigation Vessels - November 2014 edition (entry into force 1 February 2015) is that they provide „requirements for the assignment and the maintenance of class for inland navigation vessels as well as vessels operated in restricted maritime stretches of water" as stated on http://erules.veristar.com/dy/app/bootstrap.html. This perfectly suits the needs of the current project, since the ability to navigate in coastal area is listed as an advantage by the customer.

7.2 Wave Analysis

Given by BV rules is the choice of wave height a vessel is likely to encounter. Knowing that boat will operate in the coastal region of Belgium, it is possible to reference this decision to wave heights monitored over the years. The research named The Wave Climate in the Belgian Coastal Zone by (Verwaest, et al., 2008) gives insight into these wave heights and other wave related parameters, such as peak periods.

Figure 43, adapted from (Verwaest, et al., 2008) shows that maximum possible wave expected is a 1-meter wave, hence the chosen classification is IN(1,2) meaning that boat will be capable of navigating in 1,2-meter waves.

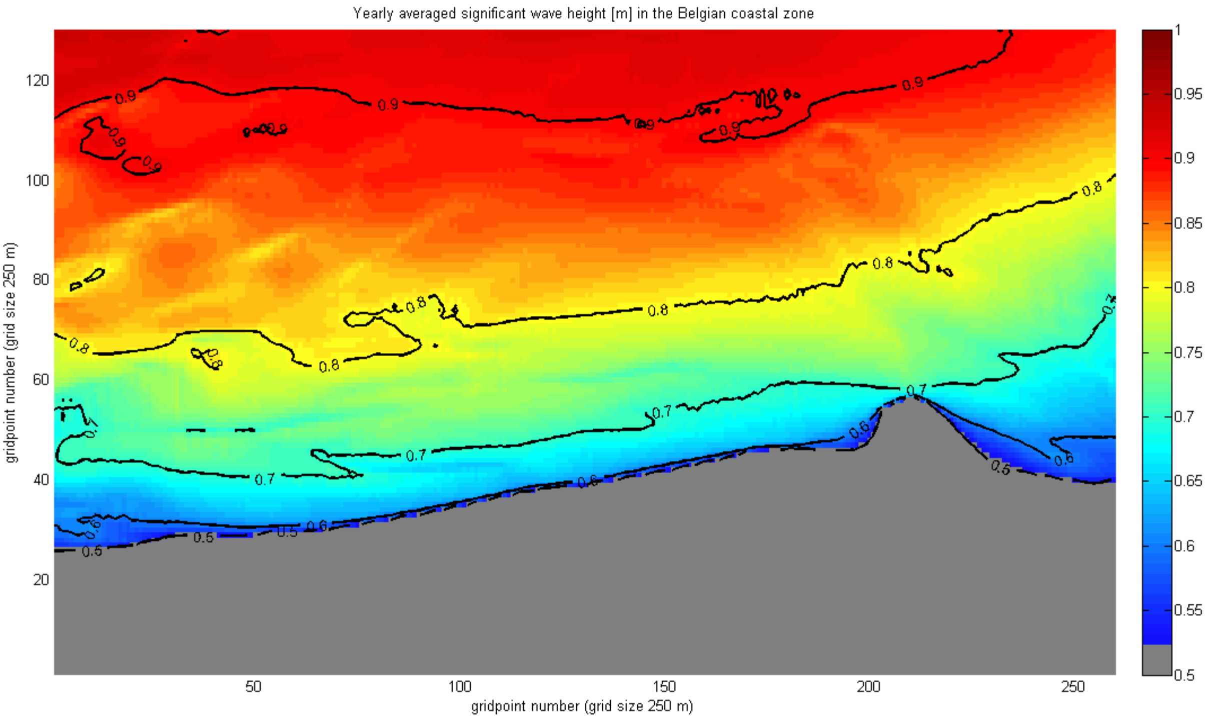

Figure 43. Wave heights in Belgian coastal area.

7.3 Material Characteristics

Before start sizing of all the structural elements, characteristics of aluminum must be determined. Special alloys used for large vessels or vessels of special needs are not required in this case, so driven by the practicality of building process and by economic insight, Aluminium of grade 5083 and O temper condition is chosen.

Grade 5083 is an aluminium-magnesium alloy that is highly resistant to damage by sea water or chemical compounds. Further, temper condition O corresponds to annealed aluminum state that retains high strength after welding. BV further says “Aluminium alloys of series 5000 in O state (annealed) are not subject to a drop in mechanical strength in the welded areas”. Finally, properties of material, as rolled product and as extruded one are in Table 4 and 5.

Table 4. Properties of rolled aluminum product.

Grade	Temper condition	Thickness t (mm)	Yield strength $R_{p\,0,2}$ min (N/mm^2)	Tensile strength R_m min or range (N/mm^2)	Elongation min (%) (1)	
					$A_{50\,mm}$	A_{5d}
5083	O / H111	$3 \leq t \leq 50$	125	275 - 350	16	14

Table 5. Properties of extruded aluminum product.

Grade	Temper condition	Thickness t (mm)	Yield strength $R_{p\,0,2}$ min (N/mm^2)	Tensile strength R_m min or range (N/mm^2)	Elongation min (%) (1) (2)	
					A_{50mm}	A_{5d}
5083	O	$3 \leq t \leq 50$	110	270 - 350	14	12

7.4 Input Data

Along with definition of material properties, calculations require primary boat data that will provide values of external loads by still water and by waves, as well as the areas supported by each structural member. A summary of that data is in Table 6.

Table 6. Particulars of the patrol boat.

Dimension		Unit		Symbol	Quantity
Length waterline at full load		m		L_{wl}	14,40
Breath waterline		m		B	3,80
Full load draught		m		T	0,75
Block coefficient				C_b	0,32
Displacement		t		Δ	13,2
Max speed		m/s		V	8,35
Frame spacing		m		l	1,2
Long stiffener spacing		m		s	0,25
Spacing of primary supporting members		m		S	0,75
Metacentric height		m		GM_{fl}	0,266
Metacentric height light ship		m		GM_{ls}	0,684
Radius of gyration		m		δ	1,33
Wave height		m		H	1,20

7.5 Dimensioning of Structural Elements

According to BV rules for Inland Navigation Vessels, Part B – Hull design and construction, Ch5 – Hull Scantlings, Sec6 – Vessels with Length L< 40 m, minimum scantling calculation is required for following members:

- Plating scantling
  - Bottom
  - Sides
  - Open deck
- Structural member scantling
  - Bottom longitudinals
  - Side longitudinals
  - Bottom girders
  - Deck girders

7.5.1 Bottom Plate

The bottom plate is calculated taking into account all the loads, Still water loads, Wave Loads and Dynamic Loads. It has also checked to fulfill other conditions set by the society regarding the keel plates, bilges and so on.

The first calculation is a Net calculation, on which safety for corrosion is added. Finally, chosen thickness is higher than the minimum due to production needs as well as increased safety.

Table 7. Bottom plate scantling.

Dimension	Unit		Symbol	Value
Reference thickness	mm		t	2,39
Addition for corrosion for bottom and side plating	mm		t_{cor}	1,75
Calculated total bottom plate thickness	mm		t	4,14
Final bottom plate thickness	mm		t_{fin}	6

7.5.2 Side Plate

The side plate is calculated in a similar manner to the previous one as longitudinally framed side structures, built with longitudinal ordinary stiffeners supported by side vertical primary supporting members.

Table 8. Side plate scantling.

Dimension	Unit		Symbol	Value
Reference thickness	mm		t	2,41
Addition for corrosion for bottom and side plating	mm		t_{cor}	1,75
Calculated total side plate thickness	mm		t	4,16
Final side plate thickness	mm		t_{fin}	6

7.5.3 Deck Plate

Deck used on board this boat is defined as a flush deck, consisting of a floor continuous over the breadth of the vessel. Calculation included taking into account deck loads and possible green water loads. Due to low waves, minimum deck loads are used.

Table 9. Deck plate scantling.

Dimension	Unit		Symbol	Value
Reference thickness	mm		t	3,16
Addition for corrosion for plating of horizontal surface	mm		t_{cor}	0,75
Calculated total deck plate thickness	mm		t	3,91
Final deck plate thickness	mm		t_{fin}	5

7.5.4 Bilge

Additionally to plating calculation, BV defines the minimum diameter of chine tubes as d=30mm. This value is adopted as a final one.

7.5.5 Bottom Structural Elements

Continuous longitudinal elements, as well as transverse frames, are calculated based on previously defined loads on different plates and taking into account length to span ratio of supported plating. Results are as follows.

Table 10. Bottom longitudinals scantling.

	Calculated value	Chosen dimension
Profile		**HP 60x5**
Modulus Z (cm3)	2,96	5,12
Shear area (cm2)	0,16	2,45

Table 11. Bottom transverse frames scantling.

	Calculated value	Chosen dimension
Profile		**T 120x6 + 60x6**
Modulus Z (cm3)	9,46	14,1
Shear area (cm2)	0,64	7,2

Table 12. Bottom girders scantling.

	Calculated value	Chosen dimension
Profile		**T 300x10 + 120x10**
Modulus Z (cm3)	272,96	278,55
Shear area (cm2)	3,62	45,0

7.5.6 Side Structural Elements

Table 13. Side longitudinals scantling.

	Calculated value	Chosen dimension
Profile		**HP 60x5**
Modulus Z (cm3)	2,20	5,12
Shear area (cm2)	0,20	2,45

7.5.7 Deck Structural Elements

Table 14. Deck longitudinals scantling.

	Calculated value	Chosen dimension
Profile		**HP 60x5**
Modulus Z (cm3)	2,36	5,12
Shear area (cm2)	0,15	2,45

Table 15. Deck girders scantling.

	Calculated value	Chosen dimension
Profile		**T 120x6 + 60x6**
Modulus Z (cm3)	8,65	14,1
Shear area (cm2)	0,58	7,2

7.6 Scantling Drawings

Drawings are made based on previous calculations and to further check the feasibility of applying this kind of structure. Drawing structure from different perspectives may uncover potential issues, as it did within the design of this boat. Drawings to be presented are the final iteration of the process.

Similar to previous sections, detailed drawings are available in Appendix.

7.6.1 Plan Drawing

Plan drawing shows the disposition of bulkheads and main features of the hull. It is obvious that structure is additionally stiffened in the aft, where the beam is wider. Additional loads coming from engines and other gear are also present in this segment of the boat.

Forepart is transversally framed due to the construction requirements.

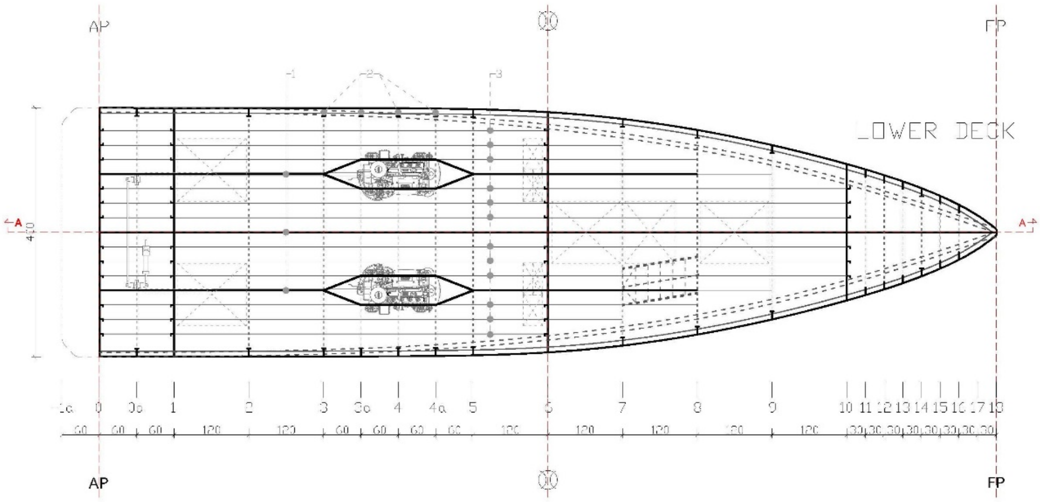

Figure 44. Plan of scantling.

7.6.2 Collision Bulkhead Frame Drawing

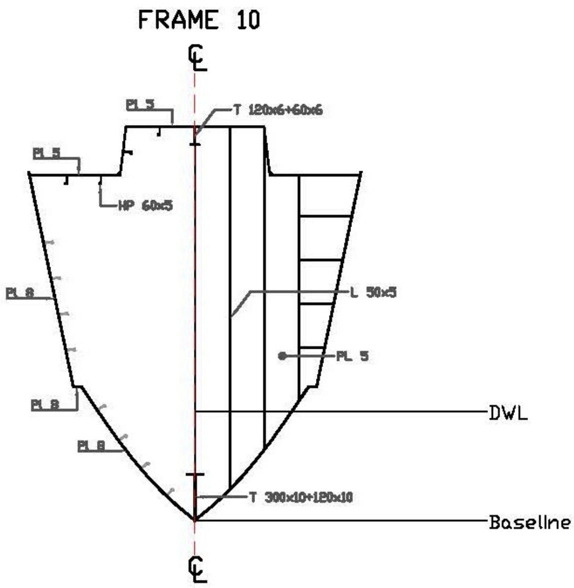

Figure 45. Disposition of Frame 10 - collision bulkhead.

7.6.3 Midship Section Drawing

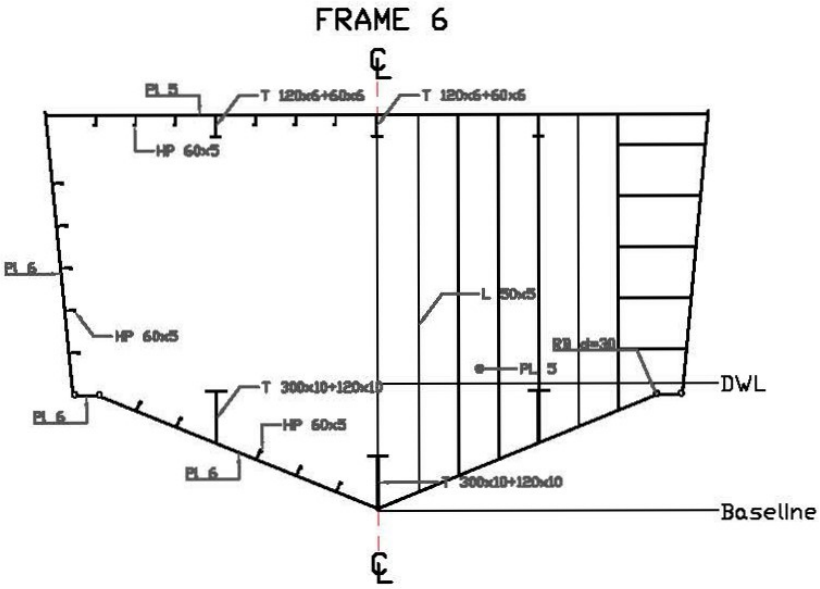

Figure 46. Disposition of Frame 6 – engine room bulkhead.

7.6.4 Engine Room Section Drawing

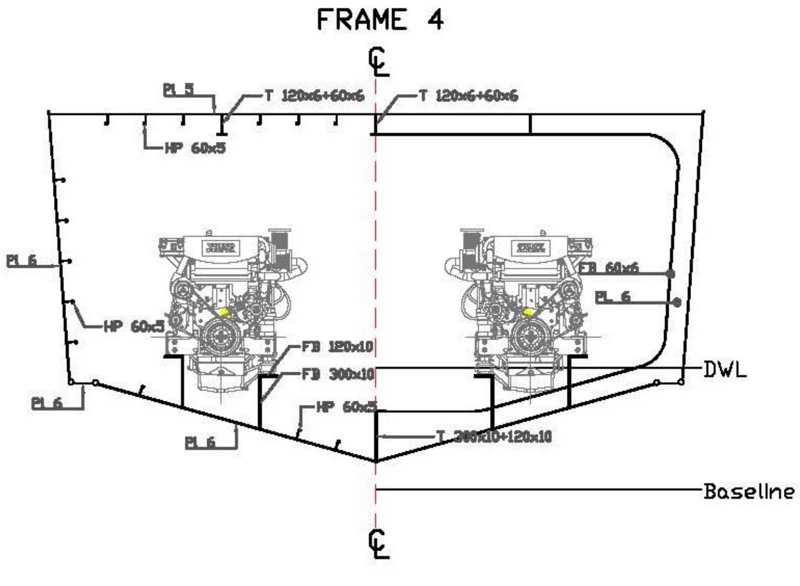

Figure 47. Disposition of Frame 4 – section through engines.

7.7 Rudder Design

This section will mainly discuss a basic dimensioning of the rudder. The rudder stock will be located at the frame 0a (aft). First, the area of the rudder should be determined. Following the recommendation of Larsson, the area of rudder for slow moving inland vessel is:

$$A = 0{,}03A_L \text{ to } 0{,}05A_L$$

Measured lateral area of patrol boat is: $A_L = 10{,}03\ m^2$.

Total chosen rudder area is then $0{,}04A_L = 0{,}4\ m^2$, which will be divided in two rudders of $A = 0{,}2\ m^2$ with a ratio aspect of 1,5, which is most suitable taking into account array of possible angles and stalling point.

Spade rudders of dimensions calculated above are very common, so the final requirements are:

- Rudder area: 0.20 m^2
- Aspect ratio: 1.5
- Span: 0.55 m
- Main chord: 0.35 m

8 WEIGHT ESTIMATION AND DEFINITION OF CENTRE OF GRAVITY.

Before calculating or defining any weights, it is critical to identify some fundamental values and principles.

As shown, chosen position of coordinate (0, 0, 0) XYZ is located:

- Horizontally, on the lowest keel position.
- Transversally, on the centerline.
- Longitudinally, on frame 0 (most aft point of the vessel).

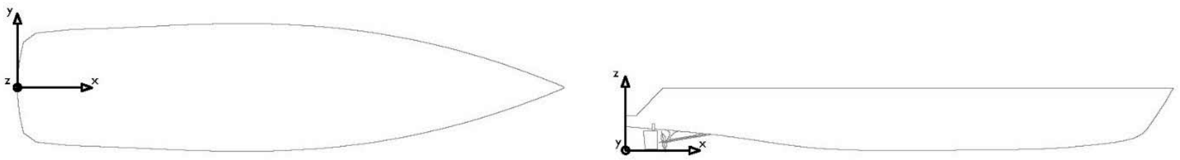

Figure 48. Position of coordinate zero.

Calculating of weights is done by implementing several different methods. Structure weight was primarily calculated using approximations based on the weight of midship section but is after replaced by more accurate calculation provided from structural 3d model made in Maxsurf. Most of other weights are calculated using Excel spreadsheets where weights of separate elements, their number and coordinates are defined.

8.1 Structure

Estimation of main structure weight was, as previously said, done in two different ways, both of those utilizing elements calculated in SCANTLING. Early in the design stage, to get some idea about possible displacement, weight was computed by calculating the weight of midship section between two frames, and multiplying that value by number of interframe sections. This method has provided fundamental value that made it possible to determine other parameters needed for the design process.

Later, a new analysis was made, with a goal to provide a more accurate estimate. Maxsurf software was used to model all structural members and to calculate their respective weights and gravity center. The result of this method is given under.
Superstructure weight was estimated in Excel software, merely listing all components included. Results are to follow.

Table 16. Structure weight.

STRUCTURE									
FEATURE	Qu	WEIGHT PER UNIT [Kg]	TOTAL WEIGHT [Kg]	L X [mm]	LY [mm]	LZ [mm]	CG X [m]	CG Y [m]	CG Z [m]
Hull structure	1	4083	4083	6646	0	925	6,50	0,00	1,34
Superstructure	1	751	751	7200	0	3500			
Windows	8	24,4	195,2	8000	0	3500			
Storage diesel oil tank	2	60,0	120,0	1800	0	932			
Lube oil tank	2	5,0	10,0	7075	0	750			
Hydraulic oil tank	2	15,0	30,0	7000	0	677			
Dirty oil tank	2	20	40,0	7000	0	608			
Fresh water tank	1	30,0	30,0	10200	0	475			
Grey water tank	1	20,0	20,0	7800	0	150			
Black water. tank	1	15,0	15,0	8850	0	150			
Chain locker	1	50,0	50,0	13800	0	1900			
Skeg + strut	2	125	250	1500	0	300			
Loading platform	1	70	70	-300	0	1550			
Brackets	0,04	1,0	223,8	7200	0	1460			
Welding	0,04	1,0	235,52	7200	0	1460			
		TOTAL WEIGHT [kg]	6123,5						

8.2 Engine Room and Machinery

Being that is very sophisticated space, engine room equipment was analyzed as a separate category. In the engine room part, all components like pumps, engines, gearboxes and so on are taken into account. Calculations and assumptions connected to the election of these elements are given in other parts of the report.

Table 17. Engine room elements weight.

ENGINE ROOM									
FEATURE	Qu	WEIGHT PER UNIT [Kg]	TOTAL WEIGHT [Kg]	L X [mm]	LY [mm]	LZ [mm]	CG X [m]	CG Y [m]	CG Z [m]
Main Engine	2	570	1140	4550	0	1009	4,30	0,00	0,90
Heat exchanger	2	20	40	4790	0	700			
Exhausts	2	115	230	5250	0	1150			
Propeller shaft	2	90	180	2520	0	370			
Propeller	2	12	24	787	0	238			
Propulsion system	1	40	40	5740	0	928			
Genset	1	404	404	2580	-450	1200			
Genset systems	1	35	35	2580	0	1200			
Main engine batteries	2	30	60	3380	0	700			
Genset battery	1	33	33	2200	620	920			
Batery bank	2	40	80	2000	540	932			
Storage diesel	2	450	900	1800	0	932			
Lube oil	2	20	40	7000	0	750			
Hydraulic oil	2	50	100	7000	0	677			
Oil Pipe	1	30	30	5100	-1500	1009			
Fuel Pipe	1	40	40	5100	1500	1009			
Hydraulic Pipe	1	80	80	3500	0	750			
Water pump	2	10	20	3670	0	550			
Water strainer	2	5	10	5650	0	600			
Air Intake/Ventilation	2	25	50	5090	0,00	1985			
Fire retardant tanks	2	40	80	6950	0	800			
Fire pump	2	15	30	6160	0	800			
Bilge pump	1	10	10	6000	0	677			
Switchboard	1	30	30	6860	40	800			
Deck wash pump	1	10	10	5000	0	1200			
Fire Wall (Insulation)	48	12	576	71190	0	1025			
		TOTAL WEIGHT [kg]	4272,0						

Following the gear present in the engine room is the steering gear located one compartment to the aft. Components of steering system are listed in the table under

Table 18. Steering Gear table

STEERING									
FEATURE	Qu	WEIGHT PER UNIT [Kg]	TOTAL WEIGHT [Kg]	L X [mm]	LY [mm]	LZ [mm]	CG X [m]	CG Y [m]	CG Z [m]
Rudders	2	51,3	102,6	488	0	159	0,8	0,0	0,4
Rudder stock	2	15	30	488	0	159			
Rudder bearings	1	10	10	488	0	159			
Electric controls	1	5	5	900	-960	550			
Hydraulic power unit	1	20	5	900	960	550			
Steering piston system	1	55	55	600	-150	900			
Bilge Pump	1	10	10	1100	0	411			
Hydraulic Pipe	1	15	15	3500	0	1500			
		TOTAL WEIGHT [kg]	232,6						

Some of the equipment is located in the storage area in the forepeak. Calculated per BV rules, anchor, chains, and motors are in this category. Calculations showed that boat would need two anchors, different in size. Also, chains and their lengths differ between main and auxiliary anchor. These elements combined with mooring equipment provide results.

Table 19. Equipment in forepeak weight.

FOREPEAK									
FEATURE	Qu	WEIGHT PER UNIT [Kg]	TOTAL WEIGHT [Kg]	L X [mm]	LY [mm]	LZ [mm]	CG X [m]	CG Y [m]	CG Z [m]
Bow anchor	1	42	42	13800	0	1800	9,88	-0,21	1,80
Bow anchor chain	1	125	125	13800	0	1800			
Bow anchor winch	1	10	10	1350	0	2100			
Stern anchor	1	10,5	10,5	600	-1250	1800			
Stern anchor chain	1	45	45	600	-1000	1800			
Mooring line 1	1	9	9	7200	0	2100			
Mooring line 2	1	6	6	7200	0	2100			
Mooring winches	2	10	20	7200	0	2100			
Bilge Pump	1	10	10	13800	0	400			
		TOTAL WEIGHT [kg]	277,5						

8.3 Outfitting

This category is, as they often are, vital and therefore very tricky to estimate. Outfitting elements weights vary widely, so picking the right ones to use is a big task. As there is almost countless number of producers and models for each member in this category

In this case, elements are divided into ones under and above the main deck.

Table 20. Interiors under deck weight.

INTERIORS									
FEATURE	Qu	WEIGHT PER UNIT [Kg]	TOTAL WEIGHT [Kg]	L X [mm]	LY [mm]	LZ [mm]	CG X [m]	CG Y [m]	CG Z [m]
Shower	1	25	25	12000	-500	700	9,0	0,1	0,9
Toilet	1	15	15	12000	520	960			
Hand wash	1	12	12	12000	100	1600			
Dishwasher	1	10	10	7850	750	960			
Stove	1	40	40	7400	750	900			
Microwave	1	15	15	8200	750	1050			
Dish locker	1	40	40	8200	750	1050			
Personal closets	6	20	120	8400	1100	1560			
Interior storage	1	50	50	9300	-720	1160			
Sofa	1	200	200	8000	-720	750			
Table	1	30	30	8000	-650	750			
Stairs	1	150	150	9000	700	1210			
Fresh Water Capacity	1	250	250	7800	0	300			
Grey Water Capacity	1	25	25	10200	0	300			
Black Water Capacity	1	25	25	10800	0	300			
Fresh water pump	1	10	10	11000	260	400			
Grey water pump	1	10	10	11000	0	400			
Black water pump	1	10	10	11000	-260	400			
Bilge Pump	1	10	10	8892	0	392			
Water Pipes	1	100	100	9991	0	470			
Calefaction System	1	100	100	9600	620	470			
Wall surfaces	1	100	100	9600	0	1500			
Floors	1	100	100	9600	0	470			
Paint - cork	65	4	260	9600	0	1500			
		TOTAL WEIGHT [kg]	1707						

Table 21. Interiors above main deck weight.

INTERIORS SUPER STRUCTURE									
FEATURE	Qu	WEIGHT PER UNIT [Kg]	TOTAL WEIGHT [Kg]	L X [mm]	LY [mm]	LZ [mm]	CG X [m]	CG Y [m]	CG Z [m]
Chairs	10	25	250	7100	-100	2470	7,4	0,0	2,7
Tables	2	20	40	6600	0	2500			
Desk	1	40	40	9000	-1100	2500			
Lamp	1	2	2	9000	100	2500			
Pilot chair	1	30	30	8400	0	2470			
Control Console	1	50	50	9000	450	2500			
Office Closet	1	30	30	5400	1000	2750			
Paint- cork	30	4	120	7800	0	3100			
GPS Antenna	1	1	1	6000	0	4200			
Radar mast	1	25	25	6000	0	4200			
Radio antenna	1	5	5	6000	0	4200			
		TOTAL WEIGHT [kg]	593						

The final category defines all the elements outside of the boundaries set for previous groups.

Table 22. Weight of miscellaneous elements.

MISCELLANEOUS									
FEATURE	Qu	WEIGHT PER UNIT [Kg]	TOTAL WEIGHT [Kg]	L X [mm]	LY [mm]	LZ [mm]	CG X [m]	CG Y [m]	CG Z [m]
Paint	150	1	150	7200	0	1450	6,7	0,0	2,0
Interior Illumination	1	5	5	7800	0	3000			
Exterior Illumination	1	5	5	7200	0	3800			
Reflector	1	15	15	9600	0	3950			
Positional Lights	3	1	3	7200	0	2000			
Electrical wire	1	200,0	200,0	7200	0	1450			
Life vest	4	1	4	7200	0	1450			
Fire Extinguisher	2	8	16	7200	0	1450			
Buoy	10	3,5	35	7200	0	2500			
Railing	1	175	175	7200	0	2300			
Crew	3	90	270	7200	0	2100			
Payload	1	500	250	3600	0	2100			
Accessories	0,2	1	737,62	7200	0	2100			
		TOTAL WEIGHT [kg]	1865,6						

8.4 Final Weight

Summary of data above gives a representation of final boat weight and the position of the center of gravity.

Table 23. Final weights and CG position.

			X	Y	Z
LIGHTSHIP WEIGHT [kg]	13210,13	TOTAL MOMENTUM [kg*m]	85482,12	12,68	17658,62
FULL WEIGHT [kg]	15070,13	TOTAL MOMENTUM [kg*m]	93401,12	12,68	19777,12

LIGHTSHIP WEIGHT [ton]	13,21
FULL WEIGHT [ton]	15,07

CG X [m]	CG Y [m]	CG Z [m]
6,471	0,001	1,337
6,198	0,001	1,312

9. ELECTRICAL ANALYSIS

This section seeks to determine a suitable electrical design for the boat. First, a load balance is obtained through Excel tables, gathering the most important electrical consumers of the boat and their particular projected daily usage. Because many DC systems have been installed, both an AC, as well as DC load balances, are calculated. Once the power requirements are known, appropriate generators and batteries are chosen.

The electrical system will be comprised of:

- Generator (Genset)
- Bank-battery for DC consumers
- Battery charger

The generator will produce the required power for the AC consumers. In addition; the battery charger will be fed by the generator. It is assumed that the batteries will be recharged in around 2 hours. The battery charger can also be fed from shore power source while standing at port, making the process less costly and more efficient. The voltage for AC will be 220 V (50 Hz) considering the connections in Belgium.

9.1 Electrical Load

Full tables with all consumers will be given in the appendix. For your consideration, final results follow.

Table 24. Load balance of DC consumers.

DC		
Feature	**Total Power (W)**	**Total Current (A)**
Exterior Lights	95,0	7,9
Interior Lights	230,0	19,2
Navigation	290,0	16,3
Equipment and systems	6750,0	412,8
Leisure	4400	29,7
TOTAL	**11770,0**	**483,9**
Safety margin	1,4	1,4
TOTAL with SM	**16470,0**	**677,5**

Table 24, above, shows the sum of power needed to run all consumers, including the safety margin that must be applied for two reasons:

- To account for possible misbehavior of source of energy used as well as that of consumers
- To provide extra power in case of need for installation of additional systems during the lifespan of the boat.

Table 25. Load balance of AC consumers.

AC		
Feature	**Current (A)**	**Total Daily Current (Ah)**
Exterior Lights	0,0	0,0
Interior Lights	0,0	0,0
Navigation	0,5	3,6
Equipment and systems	8,6	119,1
Leisure	19,6	117,0
TOTAL	**28,7**	**239,7**

AC consumer SUM gives insight at the necessary battery bank that serves as the emergency battery in case of need. According to previous, safety margin taking into account qualities of energy storage will be included.

9.2 Generator

In order to provide the highest efficiency of work and enough additional power in case of need, and based on previous results, the generator is chosen.

Marine generator set Quiet Diesel TM Series 17 QD, Model MDKBP produced by Cummins is chosen. Characteristics are in Table 26.

Table 26. Generator specification.

Nominal power	17 kW at 1.500 RPM
Peak power	200%
Nominal voltage	240 V – 70,8 A
Output frequency	50 Hz
Power factor / cos phi	1
Voltage tolerance	± 5% controlled by electronic governor
Frequency tolerance (Hz)	± 1% controlled by electronic governor

Figure 49. Generator Cummins ONAN.

9.3 Battery Bank and Charger

As previously shown, minimum battery capacity to run AC consumers for a full day is 240 Ah. Including charge/discharge capacity reduction and possibility of an improper charge, calculated size goes to 360 Ah. Batteries can be filled from the generator, since around 5kW of additional power is always available due to safety margin included, or, in the case of docking, from shore. Two 12V gel batteries with a capacity of 200Ah each will be used to store energy for usage of AC consumers.

Since the batteries are to be filled while connected to the shoreline, we will assume very short charging time of 2 hours. Previously defined, the maximum capacity of all batteries is 400 Ah so two chargers of 100 Ah, model „MASTERVOLT ChargeMaster 12/100-3" are selected. This charger uses 1,7 kW at full load, so two of them comply with the amount of residual energy made by the generator, in case of refilling when offshore.

Figure 50. Battery charger MASTERVOLT.

10. STABILITY ANALYSIS

In this section, first, the hydrostatic behavior of the vessel is checked, and afterward, the large angle stability is assessed taking into account the criteria IMO A749, accepted by Bureau Veritas Rules (Classification Society). Finally, the equilibrium for each loading conditions is computed.

10.1 Hydrostatics

The upright hydrostatics, with curves shown below, are calculated using software Maxsurf in a given condition of no heel and no trim. The curves are shown in two configurations with Figure 49 showing a change of hydrodynamic characteristics with the draft, while Figure 51 represents form curves where the dependence of form coefficients is compared to the draft.

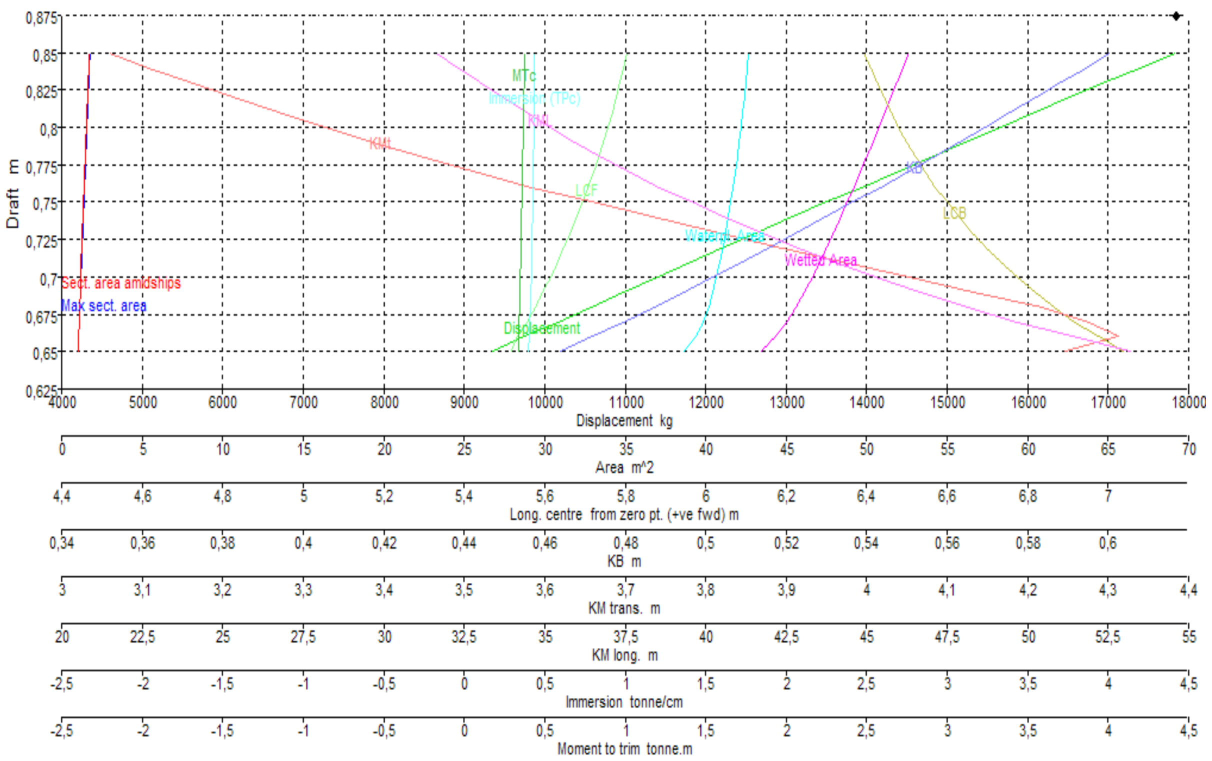

Figure 51. Hydrostatic curves.

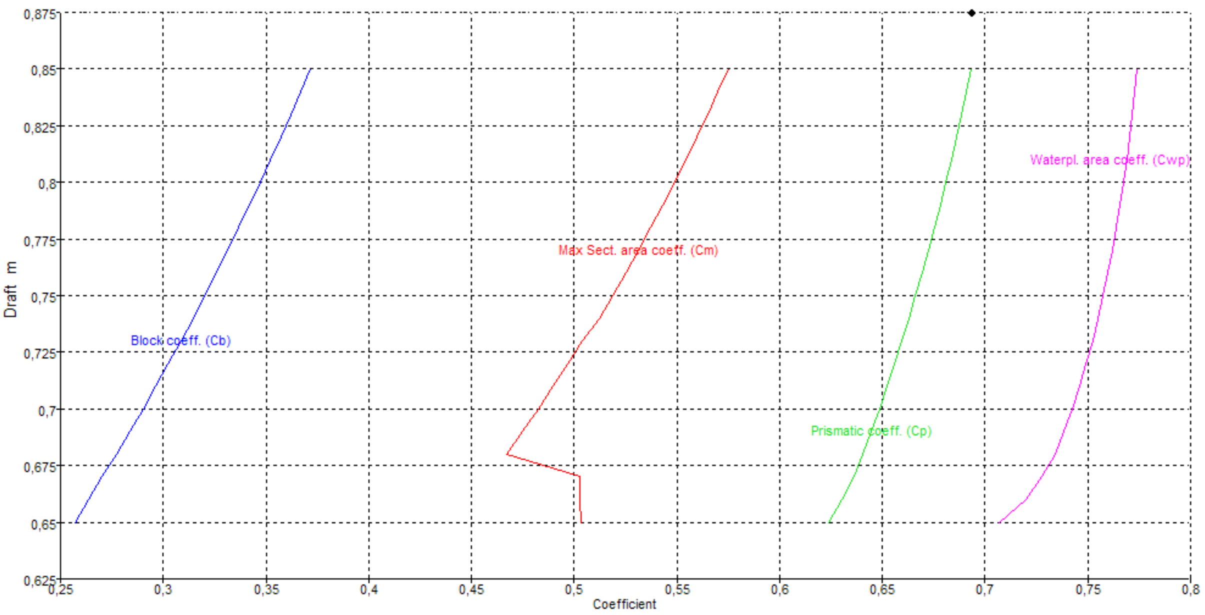

Figure 52. Form Curves.

As can be read, the analysis is done for a draft span of T_0 = 0,625 m to T_{10} = 0,875 m with original expected draft for all loading cases being in the middle of that range. The analysis step is 0,025 m, so the results are very detailed and consistent.

10.2 Large Angle Stability

Stability of the vessel was estimated in four loading configurations to provide a full set of usage data.

- In Lightship Condition only the lightship is considered, disregarding all the tanks and external loads.
- Ship in a fully loaded, Departure Condition means all the clean tanks are full to 98% capacity, and the waste tanks are at 20%.
- Mid-trip Condition means that all the tanks are full up to 50% of total capacity.
- Arrival Condition takes into account boat coming back to port with clean tanks at 10% load and waste tanks at 98%.

All the results are given in separate chapters bellow.

10.2.1 Lightship Condition

Overview of load case gives insight in weights applied:

Table 27. Lightship load case.

Item	Quantity	Total mass (kg)	LCG (m)	TCG (m)	VCG (m)
Lightship	1	13210,1	6,471	0,001	1,337
Crew	0	0,0	7,200	0,000	2,100
Payload	0	0,0	7,200	0,000	2,100
Fuel tank SB	0%	0,0	1,302	1,250	0,700
Fuel tank Port	0%	0,0	1,302	-1,250	0,700
Dirty oil SB	0%	0,0	7,144	0,500	0,276
Lubricating oil SB	0%	0,0	6,899	0,750	0,850
Lubricating oil Port	0%	0,0	6,899	-0,750	0,850
Dirty oil Port	0%	0,0	7,144	-0,500	0,276
Grey water	0%	0,0	8,216	0,000	0,065
Black water	0%	0,0	8,475	0,000	0,065
Fresh water SB	0%	0,0	9,702	0,000	0,350
Hydraulic oil SB	0%	0,0	6,856	1,000	0,474
Hydraulic oil Port	0%	0,0	6,856	-1,000	0,474
Total Loadcase		**13210,1**	**6,471**	**0,001**	**1,337**
FS correction					0,000
VCG fluid					1,337

Equilibrium state calculation for this load case yields:

Table 28. Hydrostatics in lightship load case.

Item	Value
Draft Amidships m	0,737
Displacement kg	13210
Heel deg	0,0
Draft at FP m	0,709
Draft at AP m	0,765
Draft at LCF m	0,743
Trim (+ve by stern) m	0,055
WL Length m	14,399
Beam max extents on WL m	3,814
Wetted Area m^2	48,292
Waterpl. Area m^2	41,228
Prismatic coeff. (Cp)	0,671
Block coeff. (Cb)	0,320
Max Sect. area coeff. (Cm)	0,512
Waterpl. area coeff. (Cwp)	0,751
LCB from zero pt. (+ve fwd) m	6,468
LCF from zero pt. (+ve fwd) m	5,656
KB m	0,532
KG fluid m	1,337
BMt m	3,154
BML m	39,260
GMt corrected m	2,349
GML m	38,456
KMt m	3,686
KML m	39,792
Immersion (TPc) tonne/cm	0,423

MTc tonne.m	0,353
RM at 1deg = GMt.Disp.sin(1) kg.m	541,671
Max deck inclination deg	0,2202
Trim angle (+ve by stern) deg	0,2202

Checking the stability of boat at this load case, it is noticeable that all criteria are passed with very high margins.

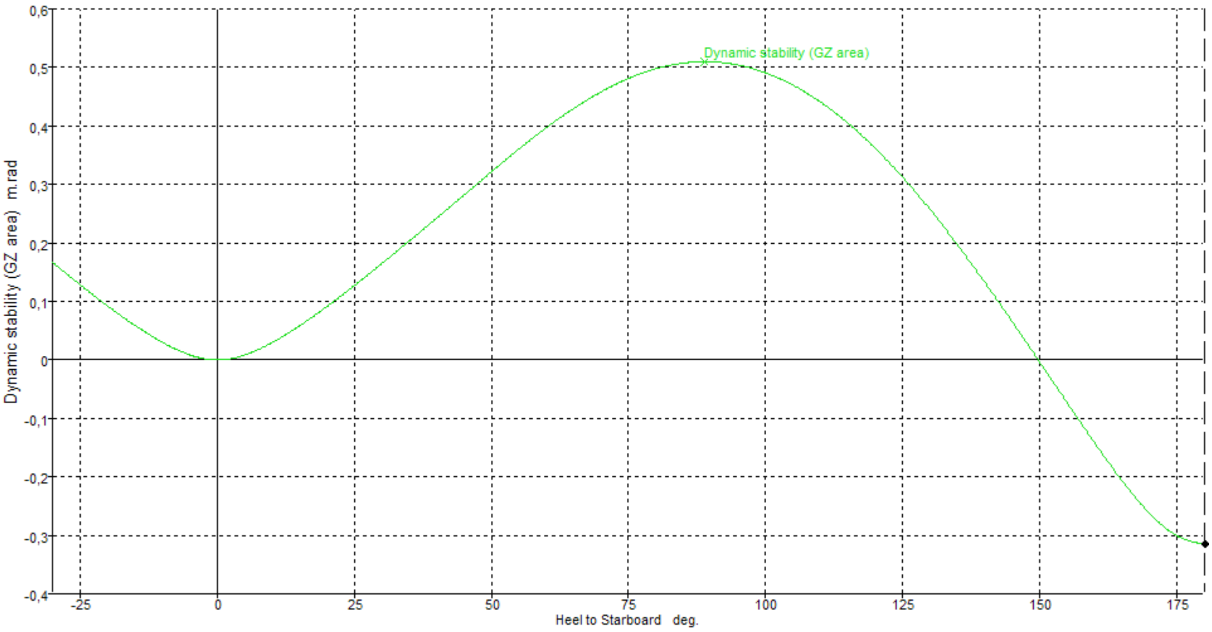

Figure 53. Dynamic stability at lightship load case.

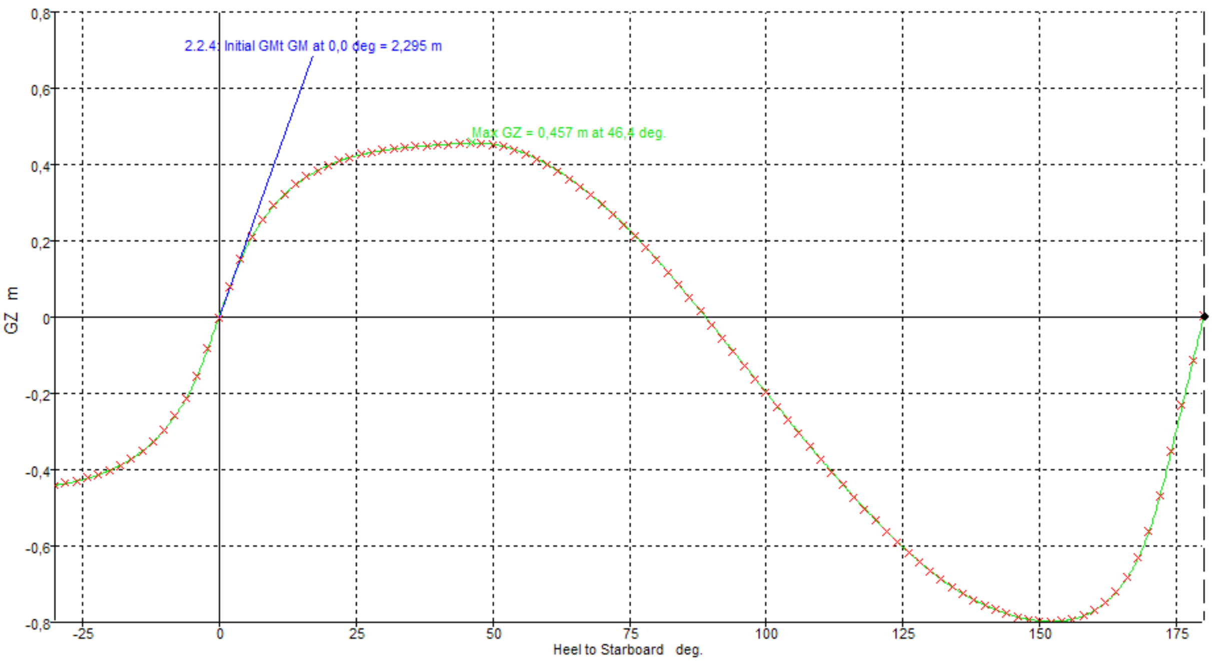

Figure 54. GZ vs. Heel curve at lightship load case.

Table 29. Stability criteria testing for lightship load case.

Criteria	Value	Units	Actual	Status	Margin %
2.2.1: Area 0 to 30				**Pass**	
from the greater of					
spec. heel angle	0,0	deg	0,0		
to the lesser of					
spec. heel angle	30,0	deg	30,0		
angle of vanishing stability	91,5	deg			
shall not be less than (>=)	0,0550	m.rad	0,1707	**Pass**	+210,43
2.2.1: Area 0 to 40				**Pass**	
from the greater of					
spec. heel angle	0,0	deg	0,0		
to the lesser of					
spec. heel angle	40,0	deg	40,0		
first downflooding angle	n/a	deg			
angle of vanishing stability	91,5	deg			
shall not be less than (>=)	0,0900	m.rad	0,2528	**Pass**	+180,91
2.2.1: Area 30 to 40				**Pass**	
from the greater of					
spec. heel angle	30,0	deg	30,0		
to the lesser of					
spec. heel angle	40,0	deg	40,0		
first downflooding angle	n/a	deg			
angle of vanishing stability	91,5	deg			
shall not be less than (>=)	0,0300	m.rad	0,0821	**Pass**	+173,59
2.2.2: Max GZ at 30 or greater				**Pass**	
in the range from the greater of					
spec. heel angle	30,0	deg	30,0		
to the lesser of					
spec. heel angle	90,0	deg			
angle of max. GZ	47,3	deg	47,3		
shall not be less than (>=)	0,200	m	0,489	**Pass**	+144,50
Intermediate values					
angle at which this GZ occurs		deg	47,3		
2.2.3: Angle of maximum GZ				**Pass**	
shall not be less than (>=)	25,0	deg	47,3	**Pass**	+89,09
2.2.4: Initial GMt				**Pass**	
spec. heel angle	0,0	deg			
shall not be less than (>=)	0,150	m	2,350	**Pass**	+1466,67

10.2.2 Departure Load Condition

Overview of load case gives insight in weights applied:

Table 30. Departure load case.

Item	Quantity	Total mass (kg)	LCG (m)	TCG (m)	VCG (m)
Lightship	1	13210,1	6,471	0,001	1,337
Crew	4	360	7,2	0	2,1
Payload	1	250	7,2	0	2,1
Fuel tank SB	98%	443,7	1,8	1,25	0,945
Fuel tank Port	98%	443,7	1,8	-1,25	0,945
Lubricating oil SB	98%	19,9	7	0,75	0,924
Lubricating oil Port	98%	19,9	7	-0,75	0,924
Dirty oil SB	20%	12,8	7	0,663	0,406
Dirty oil Port	20%	12,8	7	-0,663	0,406
Grey water	20%	35,1	7,806	0	0,149
Black water	20%	24,4	8,845	0	0,147
Fresh water SB	98%	263,8	10,199	0	0,473
Hydraulic oil SB	98%	56,2	7	1,23	0,78
Hydraulic oil Port	98%	56,2	7	-1,23	0,78
Total Loadcase		**15208,6**	**6,305**	**0,001**	**1,318**
FS correction					0,01
VCG fluid					1,328

Hydrostatic quantities for the boat at fully loaded case are:

Table 31. Hydrostatics in departure load case.

Item	Value
Draft Amidships m	0,781
Displacement kg	15209
Heel deg	0,0
Draft at FP m	0,741
Draft at AP m	0,822
Draft at LCF m	0,790
Trim (+ve by stern) m	0,081
WL Length m	14,400
Beam max extents on WL m	3,823
Wetted Area m^2	50,095
Waterpl. Area m^2	41,787
Prismatic coeff. (Cp)	0,687
Block coeff. (Cb)	0,347
Max Sect. area coeff. (Cm)	0,542
Waterpl. area coeff. (Cwp)	0,759
LCB from zero pt. (+ve fwd) m	6,302
LCF from zero pt. (+ve fwd) m	5,707
KB m	0,563
KG fluid m	1,328
BMt m	2,805
BML m	34,852
GMt corrected m	2,040
GML m	34,087
KMt m	3,368
KML m	35,415
Immersion (TPc) tonne/cm	0,428

MTc tonne.m	0,360
RM at 1deg = GMt.Disp.sin(1) kg.m	541,449
Max deck inclination deg	0,3238
Trim angle (+ve by stern) deg	0,3238

Finally, stability calculations reveal that boat is fully secure when loaded to leave port.

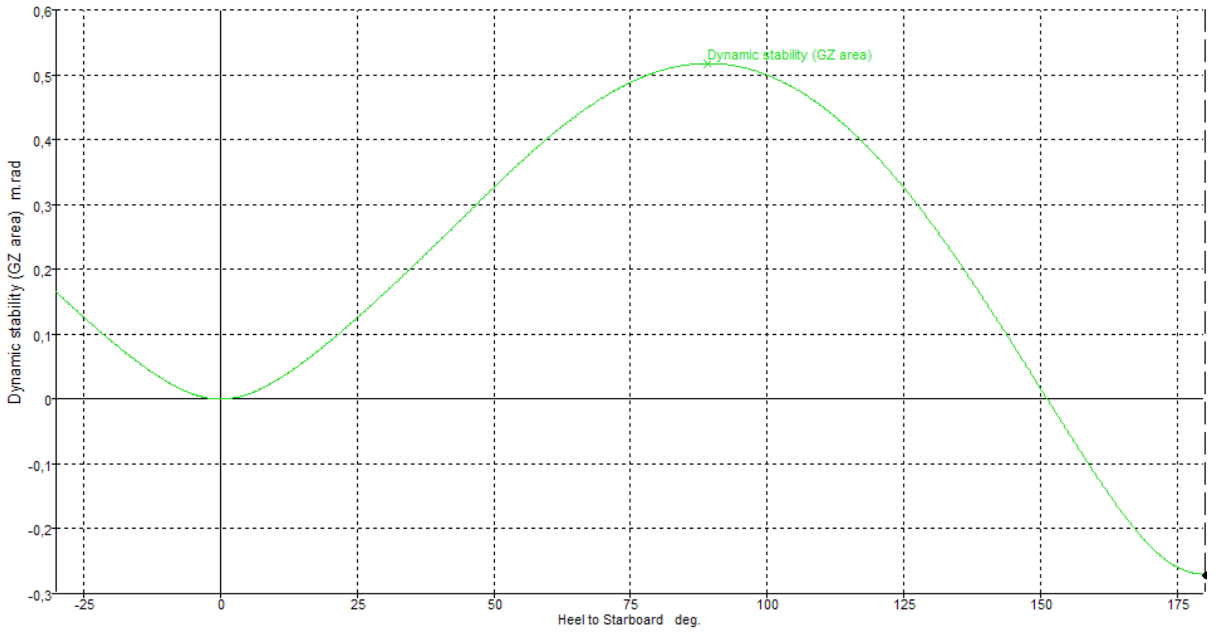

Figure 55. Dynamic stability at departure load case.

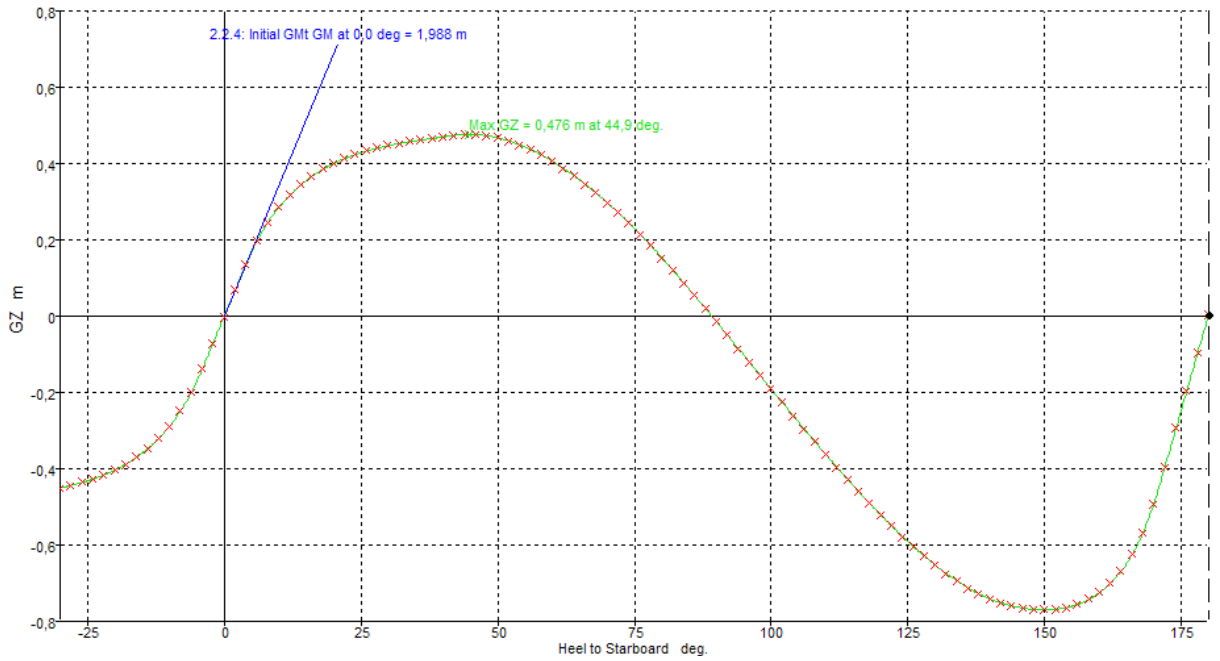

Figure 56. GZ vs. Heel curve at departure load case.

Table 32. Stability criteria testing for departure load case.

Criteria	Value	Units	Actual	Status	Margin %
2.2.1: Area 0 to 30				**Pass**	
from the greater of					
spec. heel angle	0	deg	0		
to the lesser of					
spec. heel angle	30	deg	30		
angle of vanishing stability	91,4	deg			
shall not be less than (>=)	0,055	m.rad	0,1685	**Pass**	206,37
2.2.1: Area 0 to 40				**Pass**	
from the greater of					
spec. heel angle	0	deg	0		
to the lesser of					
spec. heel angle	40	deg	40		
first downflooding angle	n/a	deg			
angle of vanishing stability	91,4	deg			
shall not be less than (>=)	0,09	m.rad	0,2521	**Pass**	180,16
2.2.1: Area 30 to 40				**Pass**	
from the greater of					
spec. heel angle	30	deg	30		
to the lesser of					
spec. heel angle	40	deg	40		
first downflooding angle	n/a	deg			
angle of vanishing stability	91,4	deg			
shall not be less than (>=)	0,03	m.rad	0,0836	**Pass**	178,8
2.2.2: Max GZ at 30 or greater				**Pass**	
in the range from the greater of					
spec. heel angle	30	deg	30		
to the lesser of					
spec. heel angle	90	deg			
angle of max. GZ	45,6	deg	45,6		
shall not be less than (>=)	0,2	m	0,501	**Pass**	150,5
Intermediate values					
angle at which this GZ occurs		deg	45,6		
2.2.3: Angle of maximum GZ				**Pass**	
shall not be less than (>=)	25	deg	45,6	**Pass**	82,54
2.2.4: Initial GMt				**Pass**	
spec. heel angle	0	deg			
shall not be less than (>=)	0,15	m	2,04	**Pass**	1260

10.2.3 Mid-Trip Load Condition

In mid-trip, loads are as shown:

Table 33. Mid-trip load case.

Item	Quantity	Total mass (kg)	LCG (m)	TCG (m)	VCG (m)
Lightship	1	13210,1	6,471	0,001	1,337
Crew	4	360	7,2	0	2,1
Payload	1	250	7,2	0	2,1
Fuel tank SB	50%	226,4	1,8	1,25	0,825
Fuel tank Port	50%	226,4	1,8	-1,25	0,825
Lubricating oil SB	50%	10,1	7	0,75	0,888
Lubricating oil Port	50%	10,1	7	-0,75	0,888
Dirty oil SB	50%	32	7	0,715	0,488
Dirty oil Port	50%	32	7	-0,715	0,488
Grey water	50%	87,6	7,8	0	0,196
Black water	50%	61,1	8,844	0	0,196
Fresh water SB	50%	134,6	10,199	0	0,413
Hydraulic oil SB	50%	28,7	6,999	1,211	0,674
Hydraulic oil Port	50%	28,7	6,999	-1,211	0,674
Total Loadcase		**14697,9**	**6,414**	**0,001**	**1,326**
FS correction					0,028
VCG fluid					1,354

Hydrostatic quantities change during traveling due to the fluids flow into and away from tanks. During mid-trip stage, amounts calculated are:

Table 34. Hydrostatics in mid-trip load case.

Item	Value
Draft Amidships m	0,773
Displacement kg	14698
Heel deg	0,0
Draft at FP m	0,750
Draft at AP m	0,796
Draft at LCF m	0,778
Trim (+ve by stern) m	0,045
WL Length m	14,400
Beam max extents on WL m	3,819
Wetted Area m^2	49,753
Waterpl. Area m^2	41,775
Prismatic coeff. (Cp)	0,680
Block coeff. (Cb)	0,339
Max Sect. area coeff. (Cm)	0,534
Waterpl. area coeff. (Cwp)	0,760
LCB from zero pt. (+ve fwd) m	6,413
LCF from zero pt. (+ve fwd) m	5,710
KB m	0,555
KG fluid m	1,354
BMt m	2,897
BML m	36,088
GMt corrected m	2,098
GML m	35,289
KMt m	3,452

KML m	36,643
Immersion (TPc) tonne/cm	0,428
MTc tonne.m	0,360
RM at 1deg = GMt.Disp.sin(1) kg.m	538,288
Max deck inclination deg	0,1809
Trim angle (+ve by stern) deg	0,1809

Applying the same stability criteria to this load case gives following results.

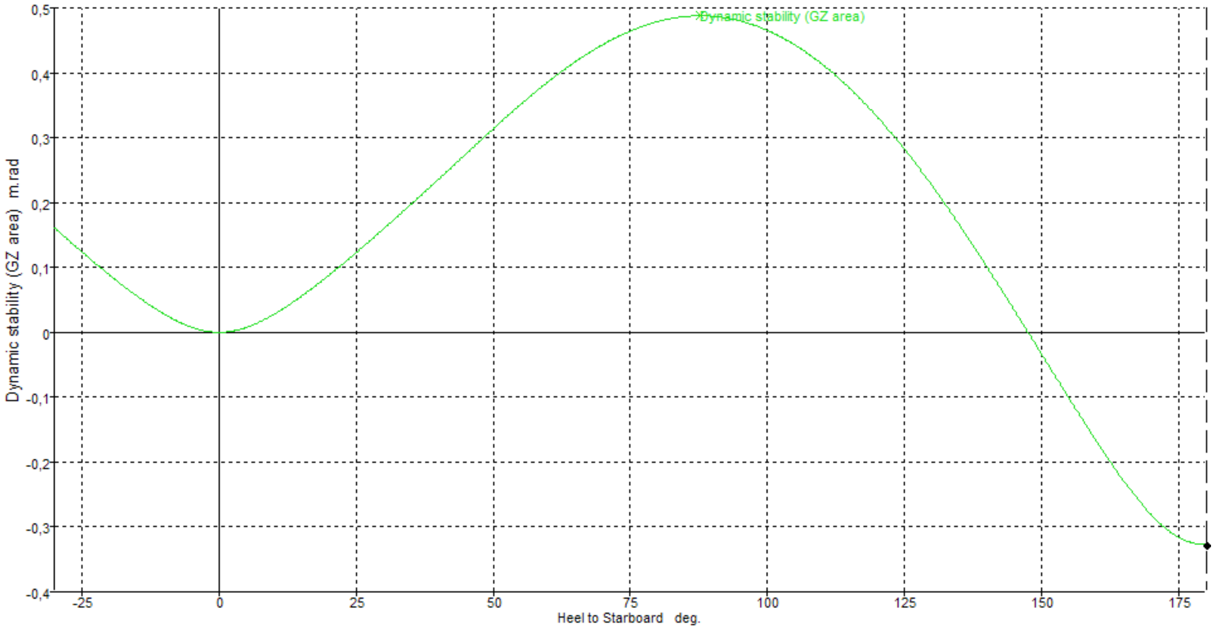

Figure 57. Dynamic stability at mid-trip load case.

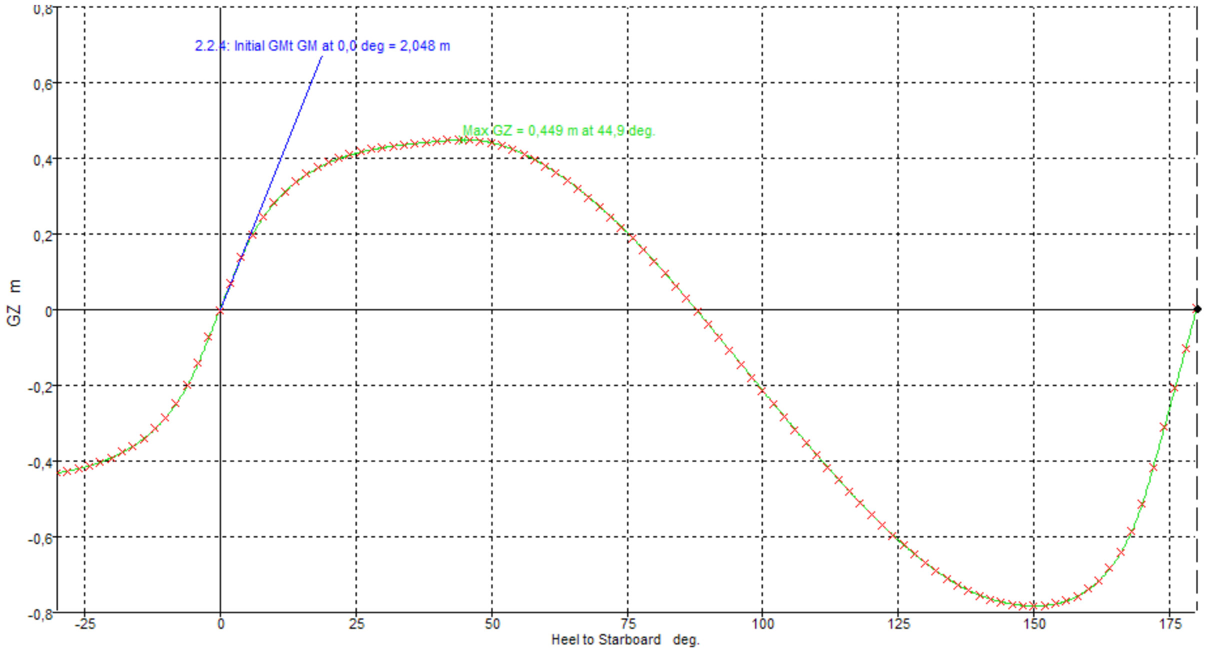

Figure 58. GZ vs. Heel curve at mid-trip load case.

Table 35. Stability criteria testing for departure load case.

Criteria	Value	Units	Actual	Status	Margin %
2.2.1: Area 0 to 30				**Pass**	
from the greater of					
spec. heel angle	0	deg	0		
to the lesser of					
spec. heel angle	30	deg	30		
angle of vanishing stability	90,1	deg			
shall not be less than (>=)	0,055	m.rad	0,1648	**Pass**	199,55
2.2.1: Area 0 to 40				**Pass**	
from the greater of					
spec. heel angle	0	deg	0		
to the lesser of					
spec. heel angle	40	deg	40		
first downflooding angle	n/a	deg			
angle of vanishing stability	90,1	deg			
shall not be less than (>=)	0,09	m.rad	0,2448	**Pass**	171,96
2.2.1: Area 30 to 40				**Pass**	
from the greater of					
spec. heel angle	30	deg	30		
to the lesser of					
spec. heel angle	40	deg	40		
first downflooding angle	n/a	deg			
angle of vanishing stability	90,1	deg			
shall not be less than (>=)	0,03	m.rad	0,08	**Pass**	166,69
2.2.2: Max GZ at 30 or greater				**Pass**	
in the range from the greater of					
spec. heel angle	30	deg	30		
to the lesser of					
spec. heel angle	90	deg			
angle of max. GZ	45,6	deg	45,6		
shall not be less than (>=)	0,2	m	0,476	**Pass**	138
Intermediate values					
angle at which this GZ occurs		deg	45,6		
2.2.3: Angle of maximum GZ				**Pass**	
shall not be less than (>=)	25	deg	45,6	**Pass**	82,54
2.2.4: Initial GMt				**Pass**	
spec. heel angle	0	deg			
shall not be less than (>=)	0,15	m	2,098	**Pass**	1298,67

10.2.4 Arrival Load Condition

Arrival condition examines boat at the time of return to port, before the discharge stage.

Table 36. Arrival load case.

Item	Quantity	Total mass (kg)	LCG (m)	TCG (m)	VCG (m)
Lightship	1	13210,1	6,471	0,001	1,337
Crew	4	360	7,2	0	2,1
Payload	1	250	7,2	0	2,1
Fuel tank SB	10%	45,3	1,799	1,25	0,725
Fuel tank Port	10%	45,3	1,799	-1,25	0,725
Lubricating oil SB	10%	2	7	0,75	0,858
Lubricating oil Port	10%	2	7	-0,75	0,858
Dirty oil SB	98%	62,8	7	0,732	0,605
Dirty oil Port	98%	62,8	7	-0,732	0,605
Grey water	98%	171,7	7,8	0	0,249
Black water	98%	119,7	8,846	0	0,249
Fresh water SB	10%	26,9	10,193	0	0,363
Hydraulic oil SB	10%	5,7	6,997	1,109	0,562
Hydraulic oil Port	10%	5,7	6,997	-1,109	0,562
Total Loadcase		**14370,2**	**6,52**	**0,001**	**1,334**
FS correction					0,018
VCG fluid					1,352

Hydrostatic quantities during a boat return to the harbor are:

Table 37. Hydrostatics in arrival load case.

Item	Value
Draft Amidships m	0,769
Displacement kg	14370
Heel deg	0,0
Draft at FP m	0,764
Draft at AP m	0,774
Draft at LCF m	0,770
Trim (+ve by stern) m	0,010
WL Length m	14,400
Beam max extents on WL m	3,815
Wetted Area m^2	49,566
Waterpl. Area m^2	41,799
Prismatic coeff. (Cp)	0,674
Block coeff. (Cb)	0,332
Max Sect. area coeff. (Cm)	0,531
Waterpl. area coeff. (Cwp)	0,761
LCB from zero pt. (+ve fwd) m	6,520
LCF from zero pt. (+ve fwd) m	5,716
KB m	0,550
KG fluid m	1,352
BMt m	2,961
BML m	37,001
GMt corrected m	2,159
GML m	36,199
KMt m	3,511
KML m	37,551
Immersion (TPc) tonne/cm	0,428

MTc tonne.m	0,361
RM at 1deg = GMt.Disp.sin(1) kg.m	541,406
Max deck inclination deg	0,0401
Trim angle (+ve by stern) deg	0,0401

As with the previous cases, the high compliance margin is present in the analysis of every stability criteria which testifies of hulls qualities.

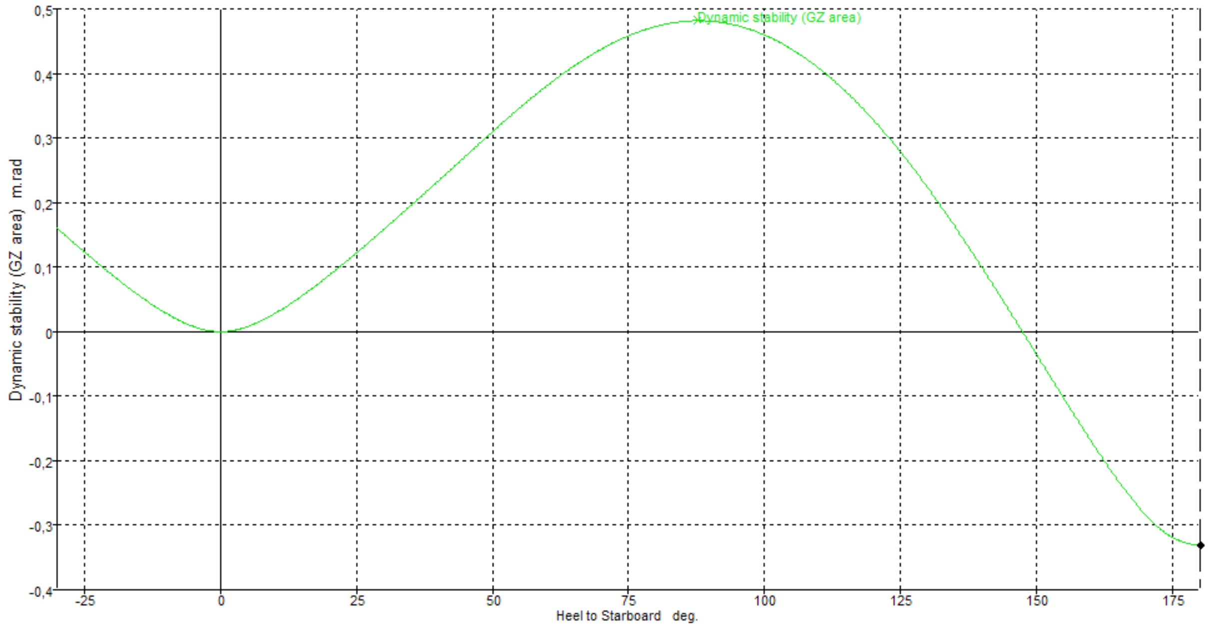

Figure 59. Dynamic stability at arrival load case.

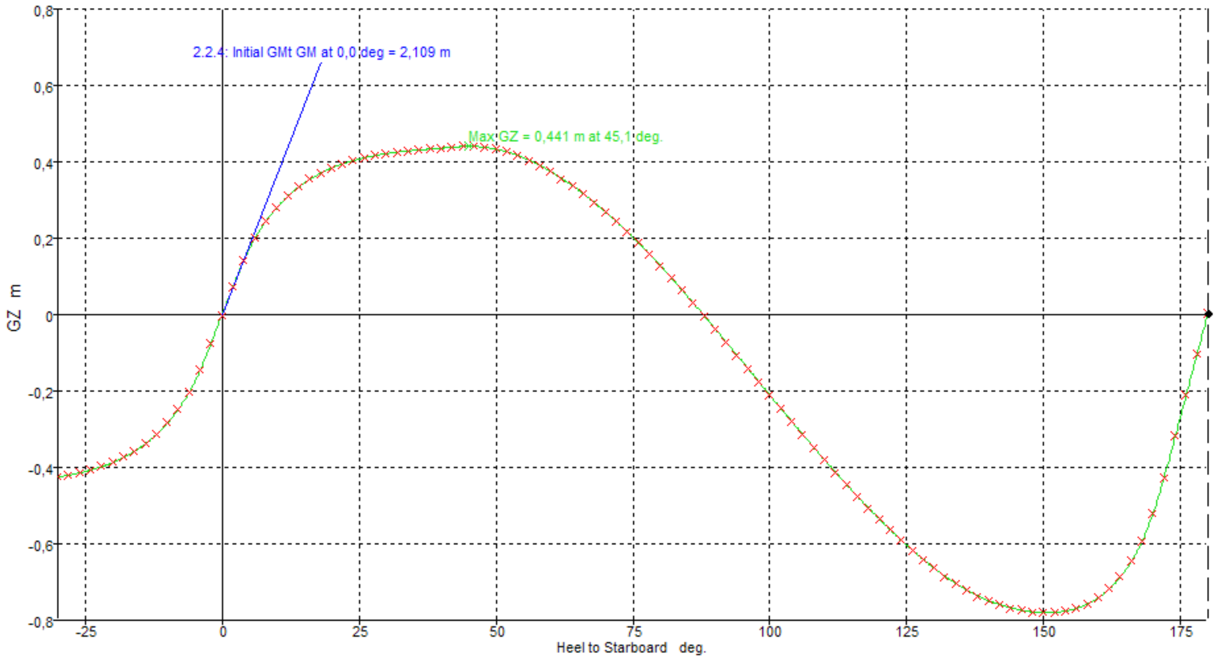

Figure 60. GZ vs. Heel curve at arrival load case.

Table 38. Stability criteria testing for arrival load case.

Criteria	Value	Units	Actual	Status	Margin %
2.2.1: Area 0 to 30				**Pass**	
from the greater of					
spec. heel angle	0	deg	0		
to the lesser of					
spec. heel angle	30	deg	30		
angle of vanishing stability	90,3	deg			
shall not be less than (>=)	0,055	m.rad	0,1639	**Pass**	197,93
2.2.1: Area 0 to 40				**Pass**	
from the greater of					
spec. heel angle	0	deg	0		
to the lesser of					
spec. heel angle	40	deg	40		
first downflooding angle	n/a	deg			
angle of vanishing stability	90,3	deg			
shall not be less than (>=)	0,09	m.rad	0,2428	**Pass**	169,8
2.2.1: Area 30 to 40				**Pass**	
from the greater of					
spec. heel angle	30	deg	30		
to the lesser of					
spec. heel angle	40	deg	40		
first downflooding angle	n/a	deg			
angle of vanishing stability	90,3	deg			
shall not be less than (>=)	0,03	m.rad	0,079	**Pass**	163,17
2.2.2: Max GZ at 30 or greater				**Pass**	
in the range from the greater of					
spec. heel angle	30	deg	30		
to the lesser of					
spec. heel angle	90	deg			
angle of max. GZ	46	deg	46		
shall not be less than (>=)	0,2	m	0,469	**Pass**	134,5
Intermediate values					
angle at which this GZ occurs		deg	46		
2.2.3: Angle of maximum GZ				**Pass**	
shall not be less than (>=)	25	deg	46	**Pass**	84
2.2.4: Initial GMt				**Pass**	
spec. heel angle	0	deg			
shall not be less than (>=)	0,15	m	2,159	**Pass**	1339,33

11. CFD TESTING AND FINAL RESULTS

The final calculation of weights allowed for final CFD testing to be done in order to confirm previously obtained results. In this point, all the data obtained made it possible to have a model with realistic motions in all degrees of freedom.

To keep the simulation simpler, only heave and pitch have been solved throughout the simulations process. This meant that inertial of the vessel need to be calculated, and weight and position of the center of gravity carefully input.

Final CFD simulation results will demonstrate how vessel behaves through different velocities and in head waves.

Meshing of the domain was done in Fine Marines proprietary mesher named Hexpress. Convergence study is done independently for the mesh convergence and time convergence. The result is the model that produces maximum residuals of order Res (U, W, P, K)) = O (10^{-3}). An example is pressure residuals in Figure 61. It is also important to say that mesh obtained for highest speed test was used in all other tests, while time step was changed for every simulation.

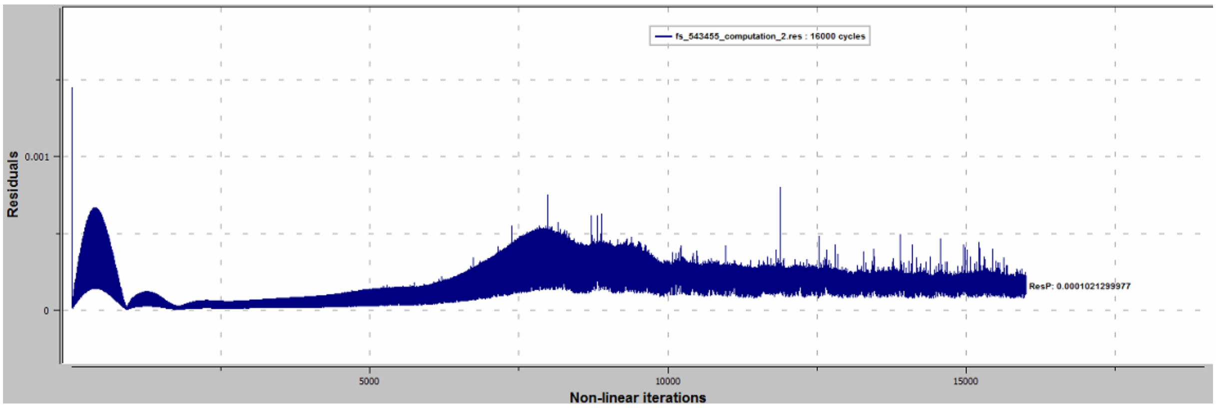

Figure 61. Residual values of pressure for Fn=0,7.

11.1 Wake and Resistance

First group of tests was done to capture free surface behind the vessel at different speeds. It also measured the resistance of the hull at all speeds.

For easier comparison, speed is made non-dimensional into Froude number. Being that maximal speed of boat corresponds to Fn=0,7 Froude numbers from Fn=0,1 to Fn=0,7 are taken into account.

Velocity is introduced to model as a ½ sinusoidal ramp (Fig 62), ending in constant speed to reduce instability issues that may occur. This meant that results obtained in this part are not admissible, due to the inability of real vessel to move in this manner.

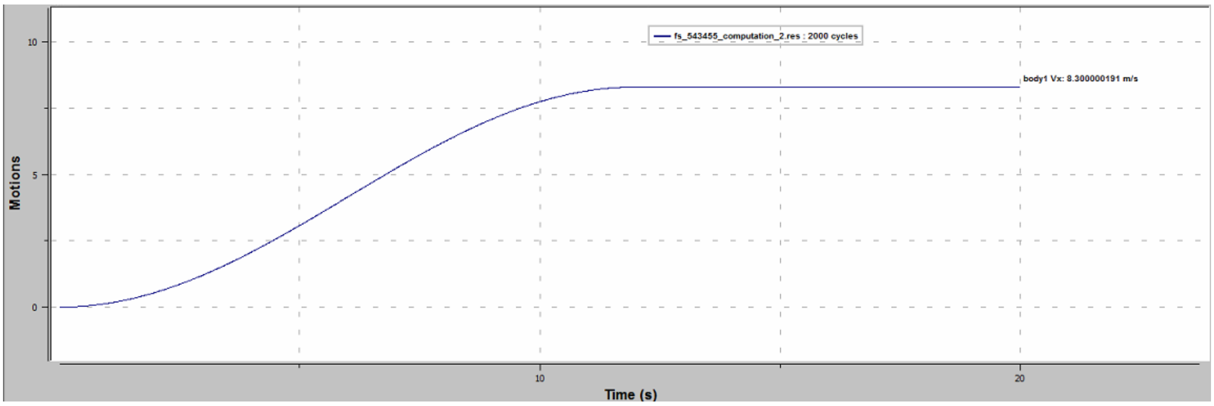

Figure 62. Velocity profile introduced into CFD model.

Eventually, results are extracted via post processing tool CFView. They can be read visually, or used as a text data to process further in other software. The principle of extraction was to create a series of sections, both parallel to the hull longitudinal axis and perpendicular to it, and analyze wave profiles on those sections.

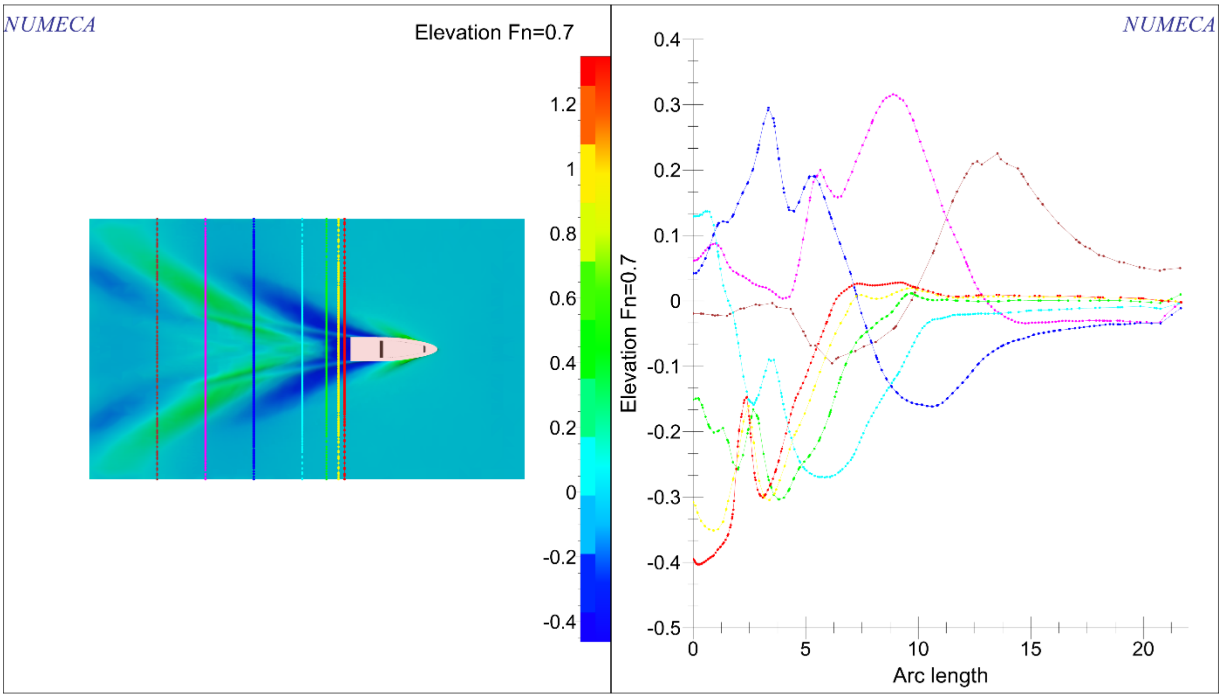

Figure 63. Wave sections produced in FineMarine postprocessor - CFView.

The data coming from CFView looks like Figure 63 and was further processed in Excel to provide a more clear comparison.

Graphs under demonstrate maximum wave heights in different longitudinal and transverse sections through Froude numbers.

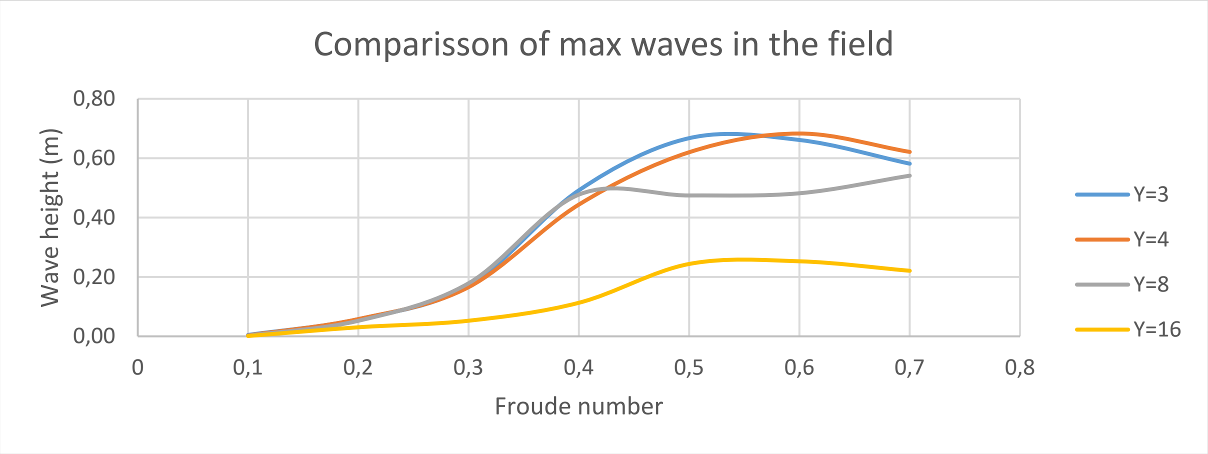

Figure 64. Longitudinal wave sections for various Froude numbers.

You may notice in the graph above that cruising speed is just before the exponential growth of wake wave heights. This is done to maximally reduce waves at the speed that boat will use most of the active time.

It is also apparent that we have maximum waves only very close to the boat (Y=3 and Y=4 correspond to 1 m and 2 m distance from the hull respectfully).

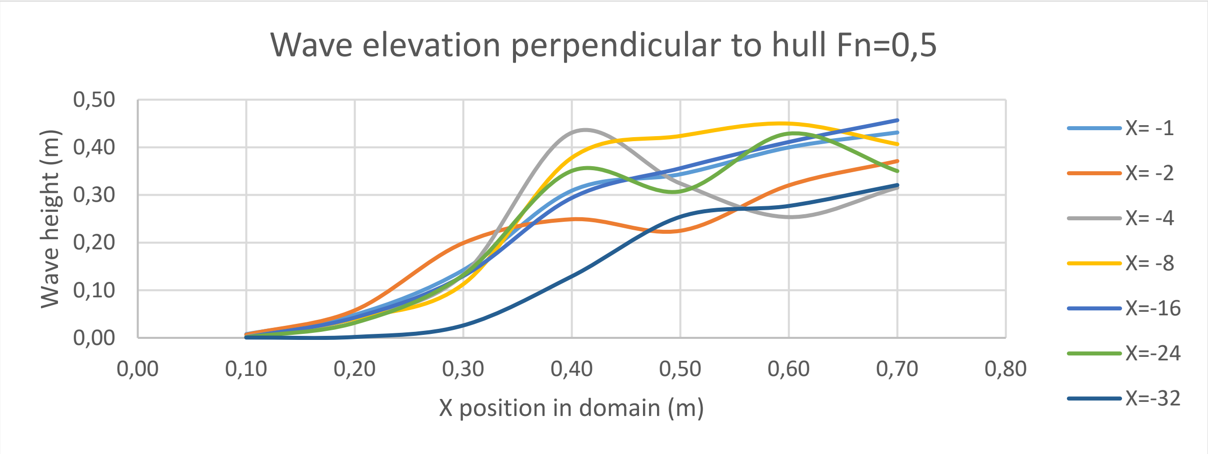

Figure 65. Transversal wave sections for different Froude numbers.

As said before, resistance and trim are also noted, and the graphs are given under.

Instead of providing charts directly from software as before, which would demonstrate resistance of half of hull, values are doubled to obtain full resistance. Compared to the previously assumed one, results are in agreement, with the remark that applying a safety margin was a correct move.

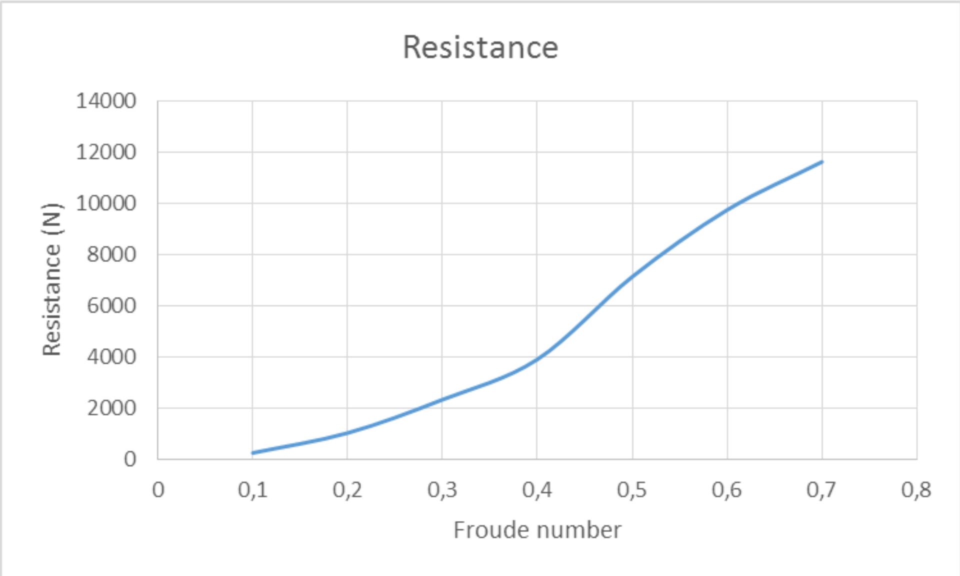

Figure 66. Resistance vs Froude number.

Also already said, the hull is designed in such a way that trim is minimized. Figure 67 shows how small are the trim changes with the change of speed. Trim is constant and almost zero all the way up to Fn = 0,5 and then it rises to around 1,6 degrees. This means that trim change due to speed change is almost negligible.

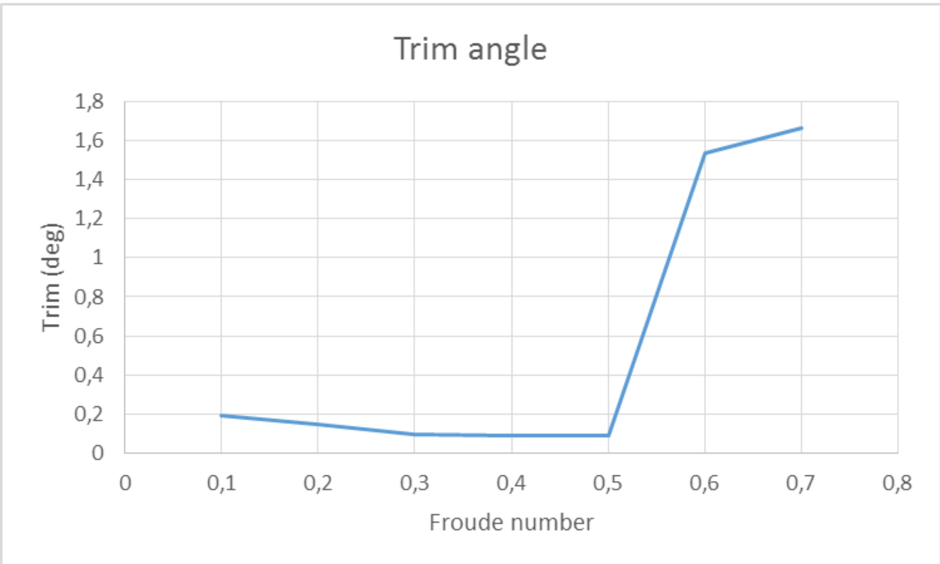

Figure 67. Trim angle vs. Froude number.

11.1.1 Wave Profiles at Cruising Speed

To check the results more in depth, two individual cases are observed. Cruising speed, 12 km/h, corresponds to Fn=0,3. The boat will be spending most of the time cruising. Therefore performance in that zone is important.

Next two figures will show wake profile at those speeds and help determine maximum values.

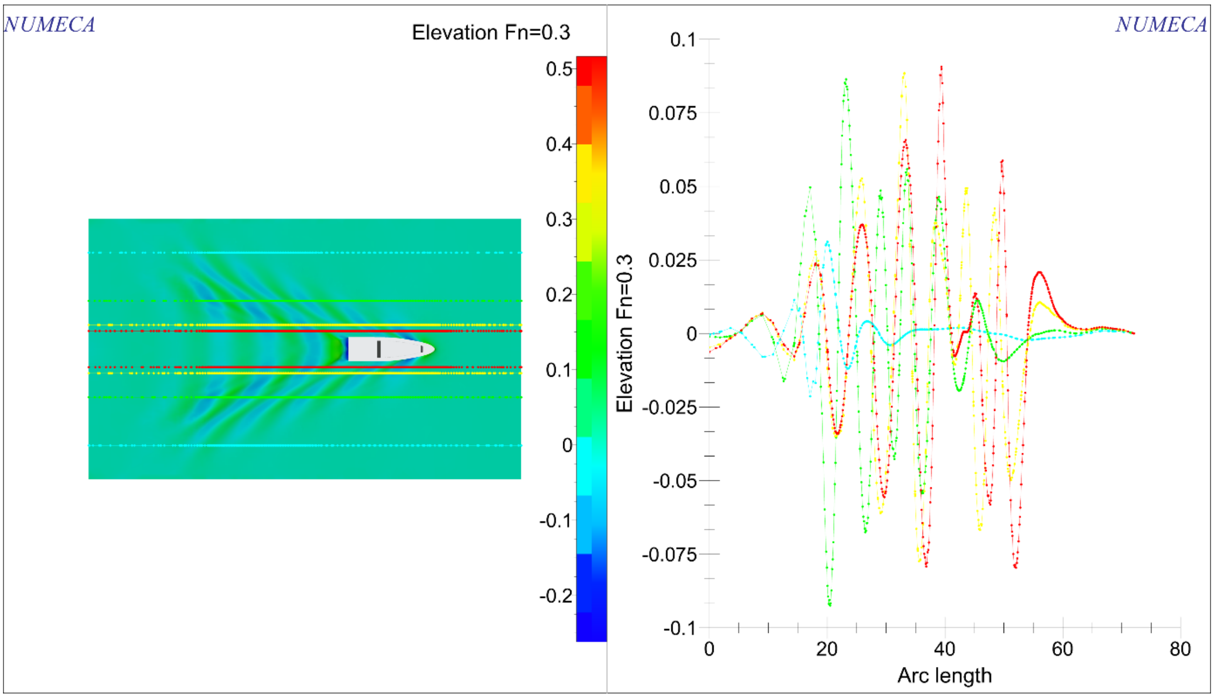

Figure 68. Wave profiles parallel to boat axis Fn=0,3.

Further analysis gives maximum wave heights along above shown sections:

- Max wave at Y=3 (one meter from the vessel) H = 0,17 m
- Max wave at Y=4 (two meters from the vessel) H = 0,16 m
- Max wave at Y=8 (six meters from the vessel) H = 0,17 m
- Max wave at Y=16 (fourteen meters from the vessel) H = 0,05 m

On the other hand, waves measured on sections perpendicular to the boat are:

- Max wave at X= -1, H = 0,14 m
- Max wave at X= -2, H = 0,19 m
- Max wave at X= -4, H = 0,13 m
- Max wave at X= -8, H = 0,11 m
- Max wave at X= -16, H = 0,13 m

- Max wave at X= -24, H = 0,13 m
- Max wave at X= -32, H = 0,02 m

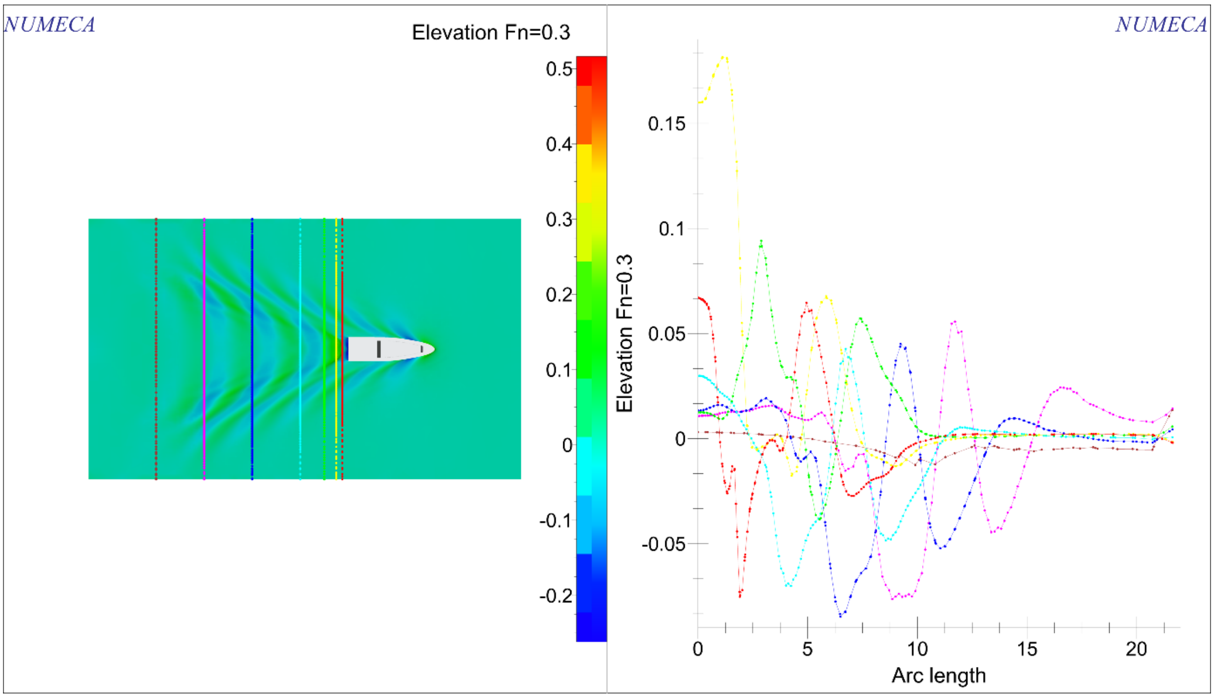

Figure 69. Wave profiles perpendicular to boat axis Fn=0,3.

11.1.2 Wave Profiles at Maximum Speed

Maximum speed produces maximum waves. Analysing only the highest wave in the field may be misleading, due to the fact those waves are usually very close to the hull and can never endanger other river users. That is why the wake field is analyzed like in the previous case.

Again, Excel analysis provides exact values.

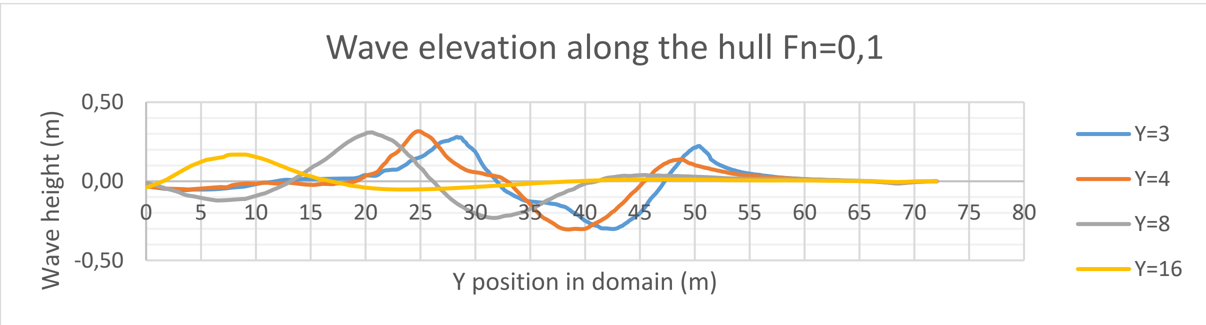

Figure 70. Wave profiles parallel to boat axis Fn=0,7.

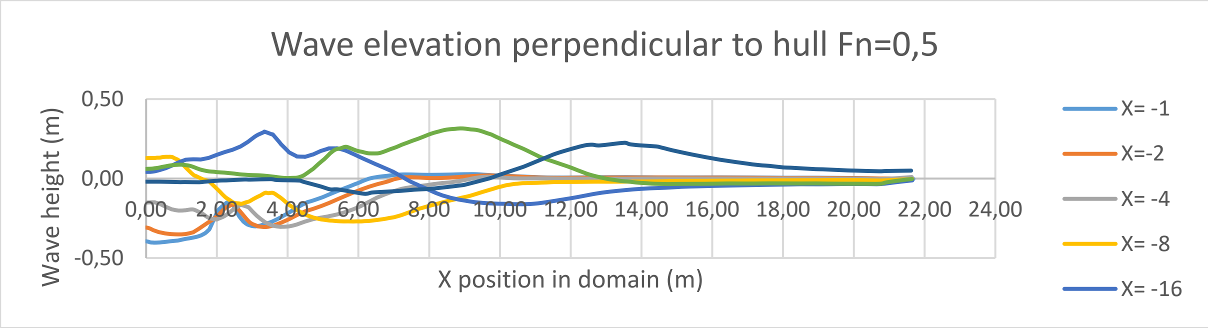

Figure 71. Wave profiles perpendicular to boat axis Fn=0,7.

- Max wave at Y=3 (one meter from the vessel) H = 0,58 m
- Max wave at Y=4 (two meters from the vessel) H = 0,62 m
- Max wave at Y=8 (six meters from the vessel) H = 0,54 m
- Max wave at Y=16 (fourteen meters from the vessel) H = 0,21 m

- Max wave at X= -1, H = 0,43 m
- Max wave at X= -2, H = 0,37 m
- Max wave at X= -4, H = 0,31 m
- Max wave at X= -8, H = 0,40 m
- Max wave at X= -16, H = 0,45 m
- Max wave at X= -24, H = 0,35 m
- Max wave at X= -32, H = 0,32 m

Results above show that with higher speed, pattern of the wake is longer and wider, but also indicate that decay of waves traveling away from the vessel is high. This means that waves in the field, away from the hull are much lower and do not exceed 0,5 meters in any direction.

11.2 Motions in Waves

When waves are introduced to the model, motions in directions other than along the axis of the vessel can be estimated. In this case, particular attention is given to heave and pitch due to previously defined attention to make vessel as calm as possible in head waves.

Since the most often encountered waves in the coastal area and estuaries are 0,6 meters high, that waves are introduced in the problem setup. In order to test the worst case scenario, wavelength coincides with the length of the vessel and the speed is kept at maximum speed, i.e. 30km/h.

Results for vertical motions and accelerations are expectedly admissible, with vessel showing a very mild response to the waves due to wave piercing bow design.

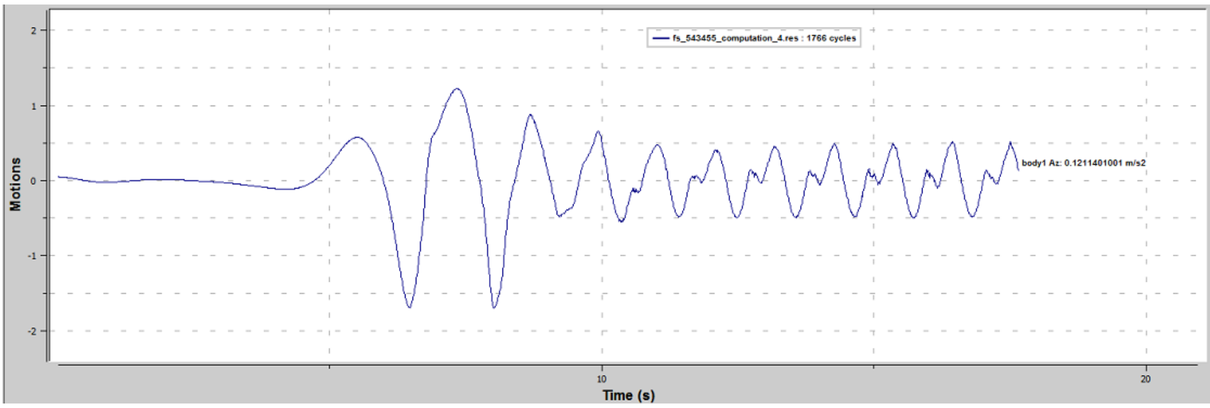

Figure 72. Vertical acceleration (m/s^2) in head waves H=0,6 m.

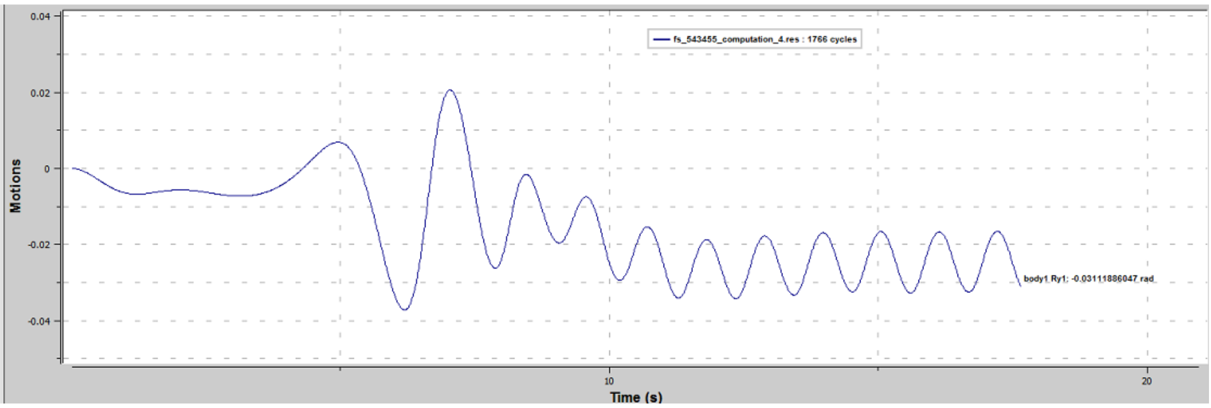

Figure 73. Pitch angle (rad) in head waves H=0,6 m.

Acceleration is limited to around 1 m/s^2 which is one order of magnitude under gravity acceleration.

Pitching angle varies through the span of 0,9 degrees with max trim angle T = 1,86 deg and min trim T = 1,0 deg.

12. CONCLUSION

Since the beginning of project, goal was to create a comprehensive design of a patrol boat characterized by exceptional qualities regarding lowering environmental impact. An extensive investigation in the field of hull design and multiple tests conducted, as well as iterations on obtained designs allowed creation of final hull shape. It proved to be 15% more efficient and produce equaly lower waves compared to the closest compared contestant, and up to 35% better than worst hulls tested in the first iteration.

Besides good results obtained for the particular case in question, steps for variating hull shape to improve design characteristics are explained and can be used as a guideline for future projects.

Although the primary goal is achieved, technical feasibility and compliance with the existing regulation have also been carefully assessed. All aspects of boat build are covered, and thesis provides high-quality insight in all characterizing qualities of the future vessel. Due to the fact that all of those directly influence previously mentioned environmental characteristics, general arrangement, weight distribution, powering and power management needed to be examined in detail so they would, in combination with the hull, create the best possible final product.

As any other boat project, this one is a complex task due to numerous tasks posed. Resolving of those is best done in iterations. Results provided within this thesis have gone through several levels on a design loop, but do not represent what would be called final project.

Finally, there are many different paths to continuing work presented above. Primarily, one could concentrate on detail project of the vessel, bringing the design loop to its end and presenting a final project. On the other hand, lack of information on hull design and hull characteristics makes it very interesting to continue exploring the influence of hull design features to mentioned set of environmental requirements. Provided enough time, building of optimization software that would cross reference all of the features defined in this work might provide new insights.

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APPENDICES

VESSEL PARTICULARS

[redacted]

Length waterline at full load	m	L_{wl}	14,40
Breath waterline	m	B	3,80
Full load draught	m	T	0,75
Block coefficient		C_b	0,32
Displacement	t	Δ	13,2
Max speed	m/s	V	8,33
Frame spacing	m	l	1,2
Long stiffener spacing	m	s	0,25
Spacing of primary supporting members	m	S	0,75
Metacentric height	m	GM_{fl}	0,266
Metacentric height light ship	m	GM_{ls}	0,684
Radius of gyration	m	δ	1,33
Wave height	m	H	1,20
Wave parameter	m	h_W	1,61
Navigation coefficient		n	1,02
Motion and acceleration parameter		a_B	0,07
Wave parameter		C	1,62

COLISION BULKHEAD

[redacted]

As per Inland navigation vessels, Ch2, Sec 1

$0,04\ L_{WL} \leq \delta_c \leq 0,04\ L_{WL} + 2$	m	$\delta_{c\ min}$	0,576
	m	$\delta_{c\ max}$	2,576

MATERIAL PROPERTIES

[redacted]

As per Alluminium Alloys, Sec 2 and Ships less than 65 or 90 m, Ch 2, Sec 3

Aluminium grade 5083

Thickness 3 < t < 50				
Yield strength	N/mm2		$R_{p\ 0,2}$	125
Tensile strength	N/mm2		R_m	270
Corrosion coefficient			λ	1,05
Local pressure coefficient for alu plating			np	1,00
Young modulus	N/mm2		E	7,E+04
Partial safety factors			Y_{W1}	1,15
			Y_{W2}	1,2
		plate	Y_R	1,2
			Y_M	1,02
		stiffeners	Y_R	1,02
			Y_M	1,02
		girders	Y_R	1,15
			Y_M	1,02
Minimum possible permissible stress from Rp 0,2min and Rm			R_{lim}	125
Material factor			k	0,8

Permissible global stresses and buckling safety

	σ_{glam}	τ_{glam}
Plating	75	50
Secondary stiffeners	75	50
Primary stiffeners	75	50

	SF
Plating	1,35
Secondary stiffeners	1,45
Primary stiffeners	1,25

Permissible local stresses and buckling safety

	σ_{locam}	τ_{locam}
Plating	81,25	
Secondary stiffeners	68,75	56,25
Primary stiffeners	56,25	50

	SF
Plating	
Secondary stiffeners	
Primary stiffeners	1,3

MOTIONS AND ACCELERATIONS

[redacted]

As per Inland navigation vessels, Ch3, Sec 3

Absolute motions and accelerations

Surge acceleration	m/s2	a_{SU}	0,50
Sway period	s	T_{SW}	2,49
Sway acceleration	m/s2	a_{SW}	0,54
Heave acceleration	m/s2	a_H	0,70
Parameter		E	2,49
Roll amplitude	rad	A_R	0,11
Roll period	s	T_R	5,67
Roll acceleration	rad/s2	a_R	0,14
Pitch amplitude	rad	A_P	0,05
Pitch period	s	T_P	2,18
Pitch acceleration	rad/s2	a_P	0,38
Yaw acceleration	rad/s2	a_Y	0,08

Relative motions

Vessel relative motion		h1	0,13

Relative accelerations

Define calculation point	m	x	0,00
	m	y	0,00
	m	z	0,00
Coefficient		K_x	0,20
X-longitudinal	m/s2	a_{x1}	0,53
		a_{x2}	0,00
Y-transverse	m/s2	a_{y1}	0,00
		a_{y2}	1,24
Z-vertical	m/s2	a_{z1}	2,54
		a_{z2}	0,35

LOADS

[redacted]

As per Inland navigation vessels, Ch3, Sec 4

Inertial local loads coeff			Y	1

River design pressure

River still water pressure	kN/m2		p_{SE}	7,36
River wave pressure	kN/m2	below wl	p_{WE}	1,02
				-7,36
	kN/m2	above wl	p_{WE}	8,68
River design pressure	kN/m2	below wl	p_E	8,58
				-1,47
	kN/m2	above wl	p_E	1,22
				-8,83
River counter pressure	kN/m2	below wl	p_{Em}	8,58
				-1,47
	kN/m2	above wl	p_E	1,22
				-8,83

Pressure on exposed decks

Pressure on main deck	kN/m2		p_E	6,825
Pressure on superstructure roof	kN/m2		p_E	1,5

BOTTOM SCANTLING

[redacted]

As per Inland navigation vessels, Ch5, Sec 2

Aspect ratio			C_a	1,07
Curvature coefficient		min	C_r	1
Plating				
Thickness 1	mm		t1	2,39
Hull girder section	cm4		I_y	1,68,E+07
Sagging bending moment	kNm		M_S	58,7
			F_{MT}	1
Water bend moment	kNm		M_W	27,83
Total vert bend moment	kNm	sagging	M_{TS}	86,53
		hogging	M_{TH}	-30,87
Hull girder notmal stress	N/mm2			0,51
			λ_L	1,00
Thickness 2	mm		t_1	0,58
Refference thickness	mm		t	2,39
Addition for corosion for bottom and side plating	mm		t_{cor}	1,75
Final bottom plate thickness	mm		t	4,14
Bilge plating				
* Square bilge with chine bars (round tube)				
Minimum tube diameter	mm		D	30
Structural members				
Ordinary stiffeners minimum web thickness	mm		t_{SWmin}	2,81
Primary supporting members min web thickness	mm		t_{GWmin}	4,01
Bottom centre and side girders span	m		l	6
Bottom centre and side girders	cm3		w	272,96
	cm2		A_{Sh}	3,62
Bottom transverses	cm3		w	9,64
	cm2		A_{Sh}	0,64
Coefficient			Km	2,53
Coefficient			Kz	1,16
Coefficient			Kmz	1,48
Coefficient			η	0,90
Bottom longitudinals	cm3		w	2,96
	cm2		A_{Sh}	0,19

SIDES SCANTLING

[redacted]

As per Inland navigation vessels, Ch5, Sec6

Aspect ratio		C_a	1,07
Curvature coefficient	min	C_r	0,50

Plating

Thickness 1	mm	t1	2,41
Addition for corosion for bottom and side plating	mm	t_{cor}	1,75
Final side plate thickness	mm	t	4,16

Structural members

Coefficient		η	0,90
Side longitudinals	cm3	w	2,20
	cm2	A_{Sh}	0,20

DECK SCANTLING

[redacted]

As per Inland navigation vessels, Ch5, Sec6

Aspect ratio		C_a	1,07
Curvature coefficient	min	C_r	0,5

Plating

Thickness 1	mm	t1	3,16
Addition for corosion for plating of horizontal surfaces	mm	t_{cor}	0,75
Final side plate thickness	mm	t	3,91

Structural members

Deck girders	cm3	w	8,65
	cm2	A_{Sh}	0,58
Coefficient		η	0,90
Deck longitudinals	cm3	w	2,36
	cm2	A_{Sh}	0,15

			ELECTRICAL BALANCE					
OPERATION VOLTAGE [V]			12			220		
FEATURE	**ITEM**	**Qu**	**POWER [W]**	**TOTAL POWER [W]**	**CURRENT [A]**	**TOTAL CURRENT [A]**	**USED TIME [h]**	**TOTAL DAILY [Ah]**
Exterior Lights	Navigation Lights (LED)	3,0	10,0	30,0	0,8	2,5	12,0	
	Emergency Lights	1,0	15,0	15,0	1,3	1,3	4,0	
	Reflector Light	1,0	50,0	50,0	4,2	4,2	4,0	
				95,0		**7,9**		
Interior Lights	Cabin Lights	10,0	10,0	100,0	0,8	8,3	12,0	
	Control Panel Lights	2,0	5,0	10,0	0,4	0,8	24,0	
	Aisle Lights	1,0	5,0	5,0	0,4	0,4	6,0	
	Galley Lights	5,0	1,0	5,0	0,1	0,4	6,0	
	Bathroom Lights	1,0	10,0	10,0	0,8	0,8	6,0	
	Steering & Engine Room Lights	10,0	10,0	100,0	0,8	8,3	4,0	
				230,0		**19,2**		
Navigation System	GPS	1,0	50,0	50,0	4,2	4,2	24,0	
	Anemometer	1,0	50,0	50,0	4,2	4,2	24,0	
	Autopilot	1,0	50,0	50,0	4,2	4,2	24,0	
	VHF	2,0	20,0	40,0	1,7	3,3	24,0	
	PC	1,0	100,0	100,0	0,5	0,5	8,0	3,6
				290,0		**16,3**		
Equipment & System	Fuel pump	2,0	250,0	500,0	20,8	41,7	4,0	
	Steering pump	1,0	250,0	250,0	20,8	20,8	24,0	
	Steering controls	1,0	150,0	150,0	12,5	12,5	24,0	
	Dirty oil pump	2,0	100,0	200,0	8,3	16,7	24,0	
	Fresh water pump	1,0	250,0	250,0	20,8	20,8	6,0	
	Fire retardant pump	2,0	750,0	1500,0	62,5	125,0	4,0	
	Bilge Pump	4,0	500,0	2000,0	41,7	166,7	4,0	
	Black & grey water pump	2,0	100,0	200,0	0,5	0,9	4,0	3,6
	Anchor windlass	2,0	350,0	700,0	1,6	3,2	2,0	6,4
	Machine space ventilation	2,0	500,0	1000,0	2,3	4,5	24,0	109,1
				6750,0		**412,8**		
Leisure	Fridge	1,0	100,0	100,0	8,3	8,3	24,0	
	Stove	1,0	1000,0	1000,0	4,5	4,5	2,0	9,1
	Microoven	1,0	750,0	750,0	3,4	3,4	1,0	3,4
	Water heater	1,0	800,0	800,0	3,6	3,6	4,0	14,5
	Sound system	1,0	200,0	200,0	0,9	0,9	8,0	7,3
	TV	1,0	50,0	50,0	0,2	0,2	4,0	0,9
	A/C & Heating	1,0	1500,0	1500,0	6,8	6,8	12,0	81,8
				4400,0		**27,9**		

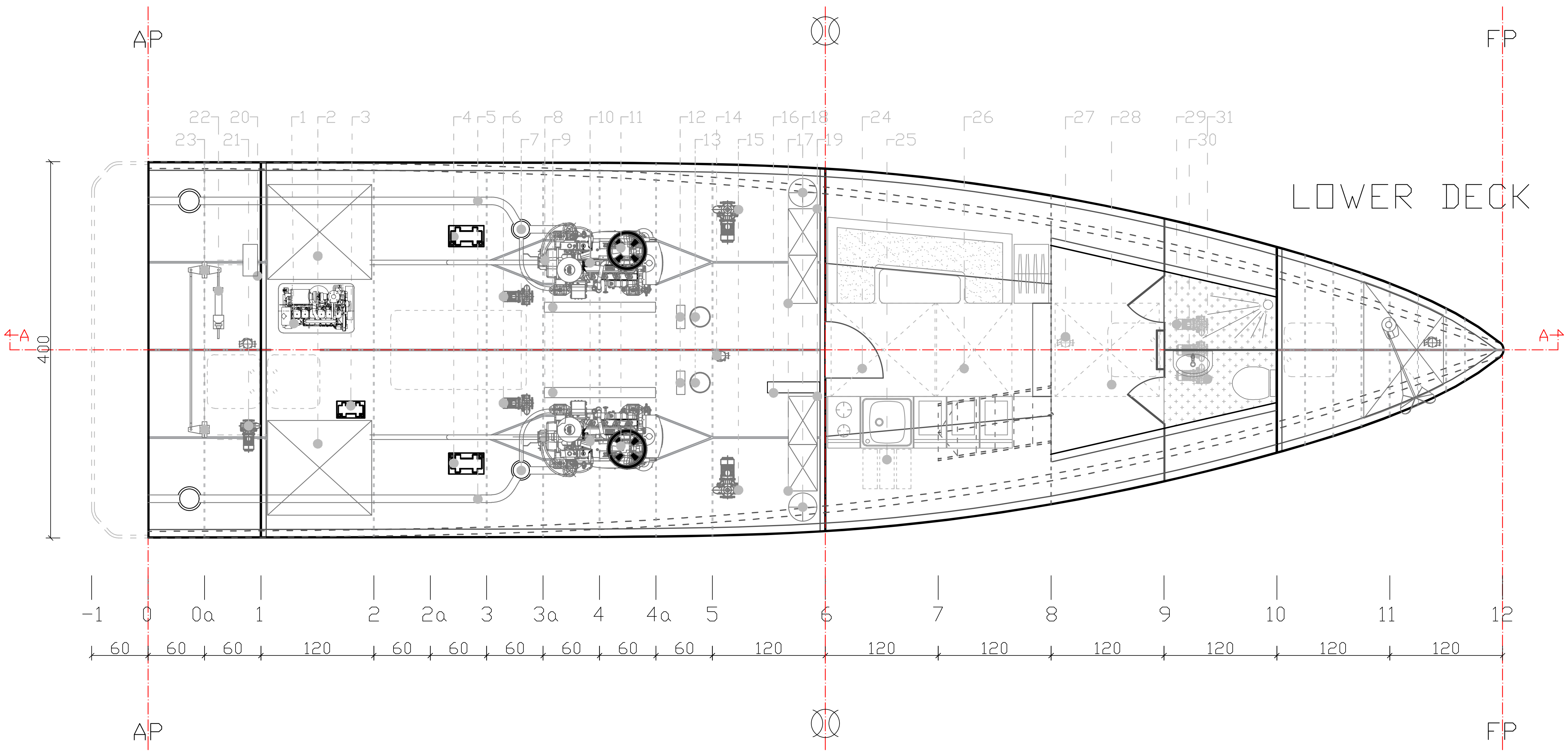
POWER [kW]	11,77	**TOTAL AT 12V [A]**	455	**DAILY for AC [Ah]**	240
Safety Factor	1,4	**TOTAL AT 220V [A]**	28,6	Corr. for low charge and aging	1,5
TOTAL POWER [kW]	16,47			**AC SYSTEMS BATTERY [Ah]**	360

RADOMIR JAŠIĆ

DESIGN OF A LOW WASH INLAND PATROL BOAT

Lower Deck Plan
Scale 1:50

ITEM NO	ITEM
1	GEN-SET
2	MAIN FUEL TANK
3	GEN-SET BATTERY
4	MAIN ENG.BATTERY
5	EXAUST WITH WATER LOCK
6	WATER PUMP
7	MUFFLER
8	GEAR BOX
9	HEAT EXCHANGER
10	MAIN ENGINE
11	ENGINE ROOM SUPPLY FAN
12	STRAINER
13	SEA CHEST
14	BILGE PUMP
15	FIRE PUMP
16	SWITCH BOARD
17	LUBRICATING OIL TANK / DIRTY OIL
18	FIRE EXT. SYSTEM
19	HYDRAULIC OIL TANK
20	ELECTRONIC STEARING CONTROL UNIT
21	STEERING HYDR. POWER UN.
22	STEERING GEAR
23	RUDDER STOCK
24	GRAY WATER TANK
25	AIR CON. SYSTEM
26	BLACK WATER TANK
27	BILGE PUMP
28	FRESH WATER TANK
29	FRESH WATER PUMP
30	GREY WATER PUMP
31	BLACK WATER PUMP



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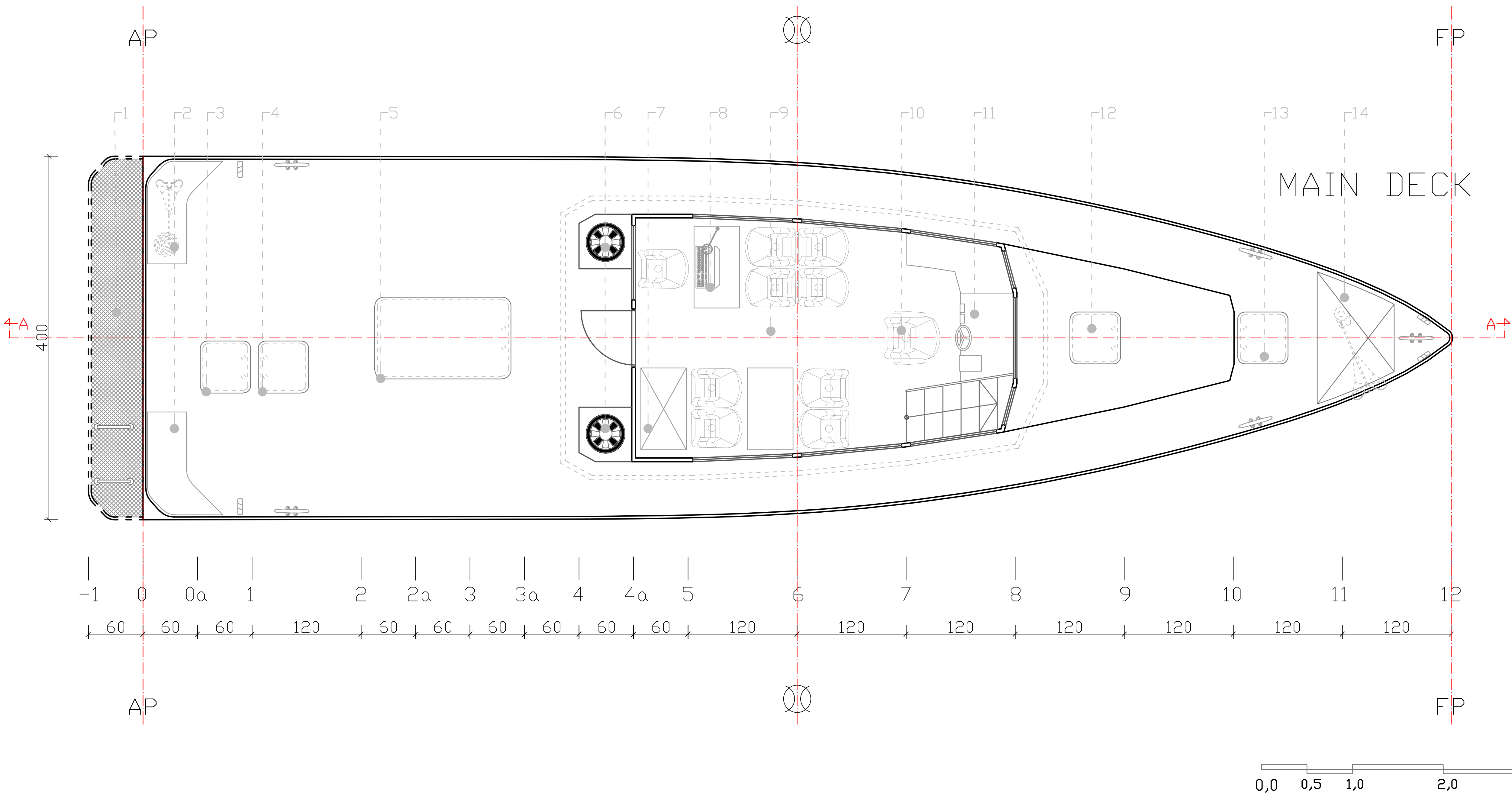
DESIGN OF A LOW WASH INLAND PATROL BOAT

Main Deck Plan
Scale 1:50

ITEM NO	ITEM
1	AFT ACCESS PLATFORM
2	DECK LOCKERS /SEATS
3	FLUSH HATCH - STEARING ROOM
4	FLUSH HATCH - ENGINE ROOM
5	ENGINE SERVICE HATCH
6	VENTILATION
7	UTILITY LOCKER
8	PC
9	CABIN AREA
10	COCKPIT
11	CONTROLS
12	FLUSH HATCH - GALLEY
13	FLUSH HATCH - FORE PEAK
14	BOW ANCHOR LOCKER



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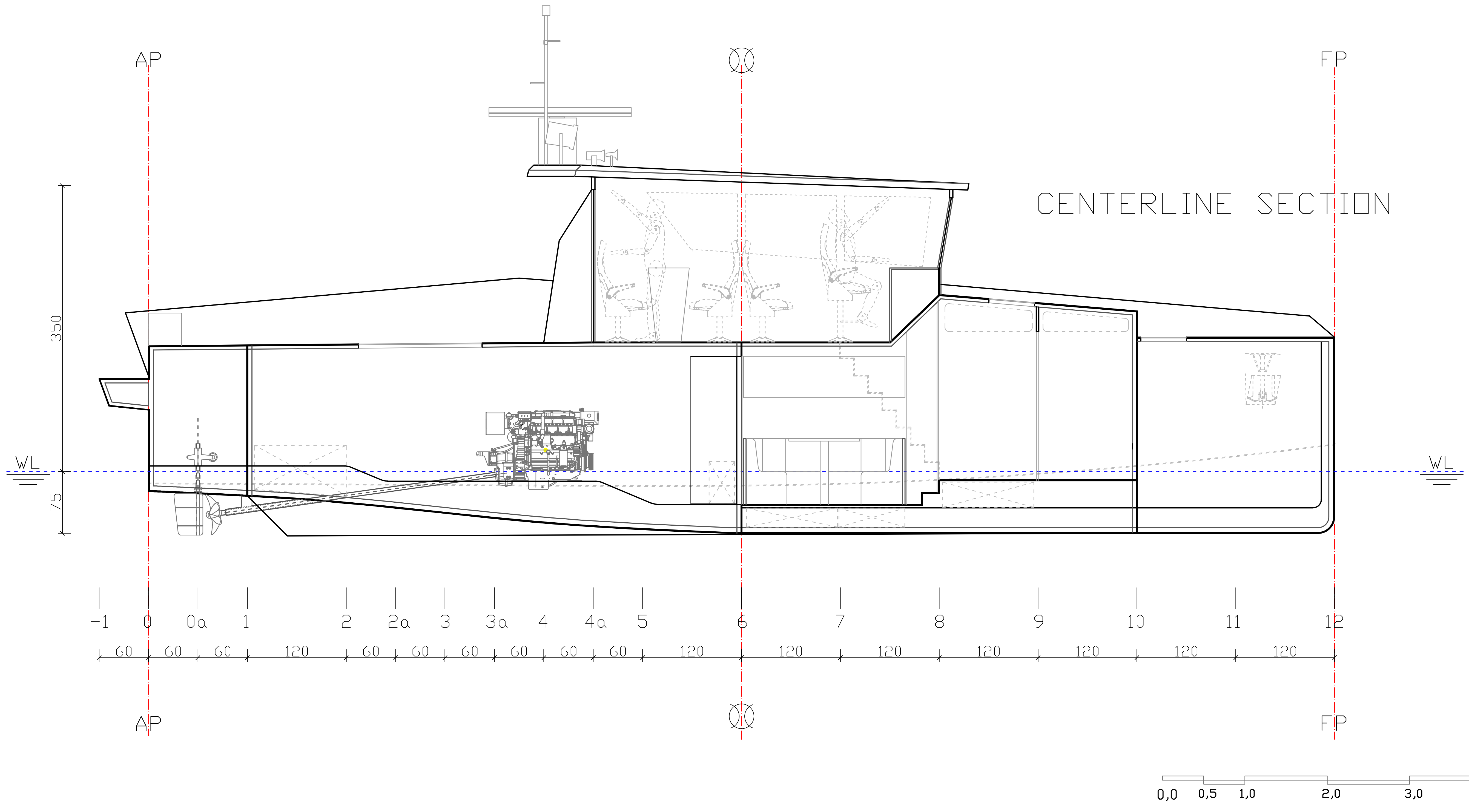
DESIGN OF A LOW WASH
INLAND PATROL BOAT

Center Line Section
Scale 1:50



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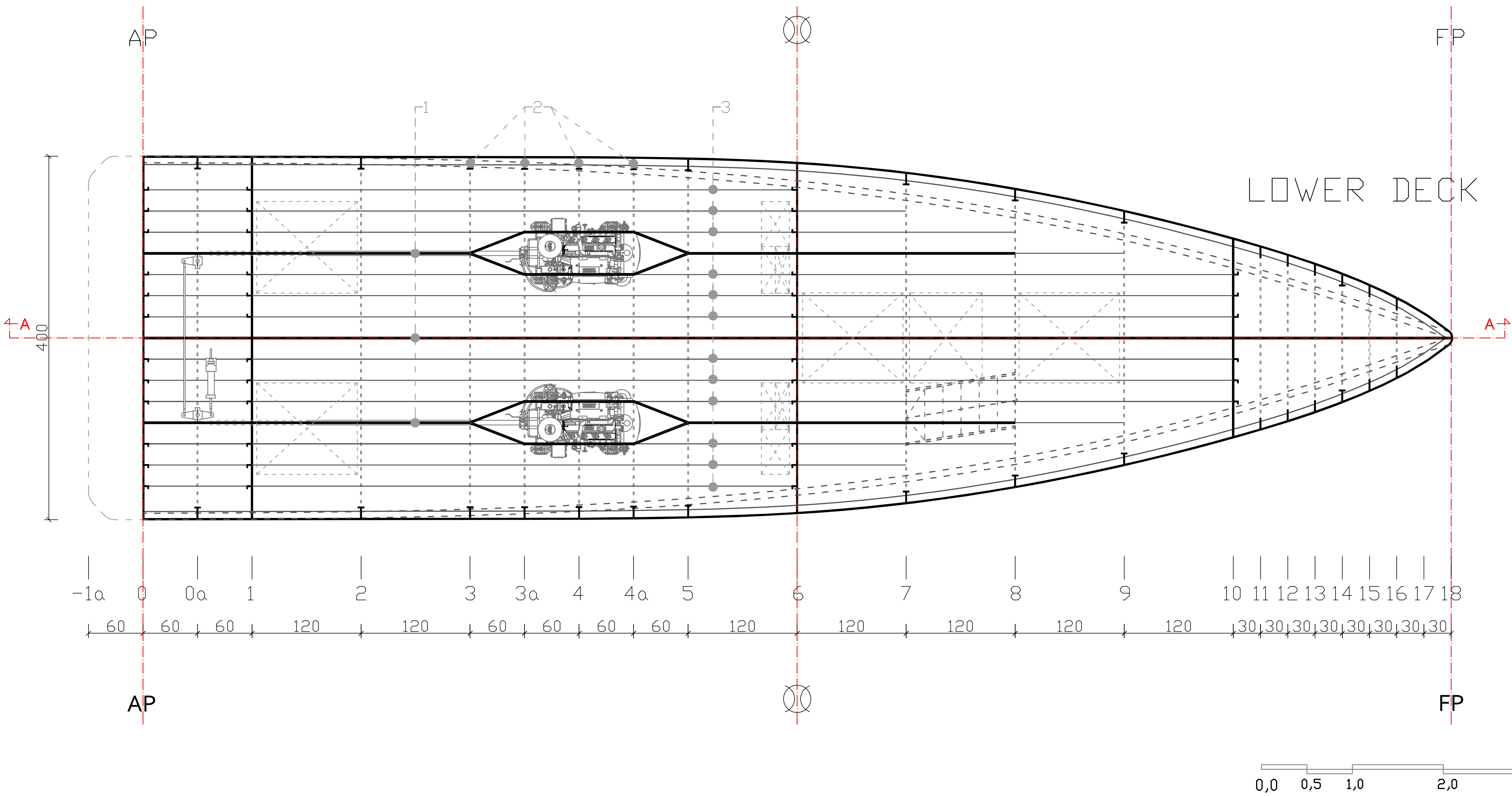
DESIGN OF A LOW WASH INLAND PATROL BOAT

Scantling - Plan
Scale 1:50

ITEM NO	ITEM
1	BOTTOM GIRDERS - T 300x10+120x10
2	TRANSVERSE FRAMES - T 120X6+60x6
3	BOTTOM STIFFENERS - HP 60x5



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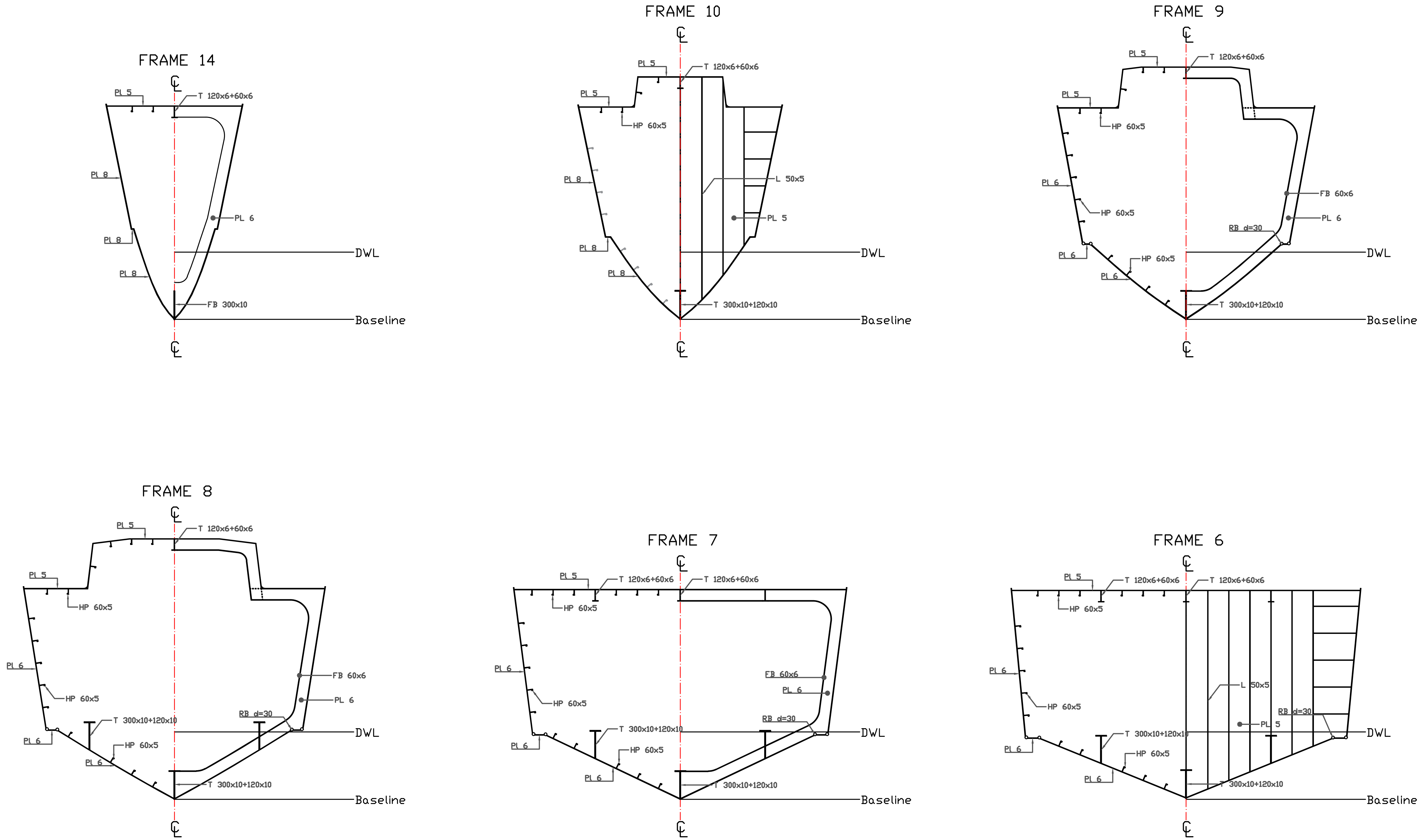
DESIGN OF A LOW WASH INLAND PATROL BOAT

Scantling - Frames
Scale 1:50



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DESIGN OF A LOW WASH
INLAND PATROL BOAT

Scantling - Frames
Scale 1:50