Ballastless sailing

Sailing without ballast water, using upthrusting air

Project Members:
Charlotte van der Wal 0861546
Silvio Monteiro de Queiróz 0848582
Sander Smienk 0863594
Mike Poelman 0858906
Tim van Suijlekom 0859492

Principal:
Mr. Van Kluijven

Expert:
Mrs. Van der Valk

Rotterdam Mainport University

28-3-2014
Management review

**Why no ballast water?**
Invasive marine species are carried to different parts of the world by ships’ ballast tanks; this often causes harm to regional marine species. This is irreversible, which makes finding a solution to sail without ballast water an important job. The essence of the report is to find a solution to the problem of the contamination and deteriorating of the environment. Especially the salt water that is being carried from A to B causes this problem. To stop this problem the goal is to create a ballastless vessel, thus using air. Because the marine species are carried in water and because the system will use air and not water, the species won’t be transported across the world. This report describes the research in using upthrusting air to sail without ballast water.

**Floating tanks**
The upthrusting force is completely based on adding more buoyancy to a vessel. Instead of bringing the ship down with ballast water, the system will bring her up with air, using tanks attached to the side of the vessel. Keep in mind that the vessel has a larger draft than normal vessels before engaging the tanks. This system will eliminate the pollution caused by ballast water. The floatation tanks were chosen to solve the problem. The design of the newly researched system consists of ten floating tanks, five on each side of the ship. Using an alloy of graphene and polypropylene to make these tanks, the weaknesses and strengths of each material would be eliminated. More or less force will be created by moving the tanks up or down vertically along the side of the ship with the use of hydraulic engines. This system can operate fully automatically with a system designed by us with the use of existing components. A centralized controlling system will guide this. Numerous transmitters will compare, measure and send their information about the state of the vessel to the main load master computer. The computer will send a signal to the hydraulic system which will move the tanks. Pins secure the tanks so they will not detach from the vessel. If the tanks would come off, it would be disastrous, so advantages and disadvantages need to be considered. For more detail see 1.2.1 separate floatation tanks page 9.

**The difference**
This tank system is a passive system. The systems you have nowadays, like ballast water treatment systems have their own power requirements, fuel consumption and emission in which it is unclear if the environment is impacted positively or negatively. Also the treatment systems doesn’t treat the water 100% and our system won’t transport any marine species. While conducting our research, the reaction of the ship on heavy weather has not been tested.

**The conclusion**
The system that has been researched has a high potential of succeeding in which there is no chance of bringing any species around the world. Of course the safety of the crew is a top priority so the logical next step would be to investigate how the safety and security can be maintained on board. The commercial part of this idea needs to be looked at as well. One of the most important things for ship-owners to know is if the costs of the new system is profitable on short or long term, compared to the ballast water treatment systems.
# Table of Contents

Management review ........................................................................................................................................ 2

Why no ballast water? .................................................................................................................................. 2

Floating tanks ................................................................................................................................................ 2

The difference .................................................................................................................................................. 2

The conclusion .................................................................................................................................................. 2

Preface ............................................................................................................................................................. 5

Introduction ...................................................................................................................................................... 6

The main objective ......................................................................................................................................... 6

Main- and sub questions ................................................................................................................................. 6

Project borders ............................................................................................................................................... 6

Research methodology ................................................................................................................................... 6

Desk and field research .................................................................................................................................. 6

1. The design .................................................................................................................................................. 7

1.1 Ballast water ............................................................................................................................................ 7

1.2 Concepts .................................................................................................................................................. 9

1.2.1 Separate floatation tanks .................................................................................................................. 9

1.2.1.1 Tank moving mechanism .............................................................................................................. 9

1.2.2 Large floatation tanks ..................................................................................................................... 10

1.2.3 Compression units ............................................................................................................................ 12

The advantages and disadvantages of every concept ..................................................................................... 13

1.2.4 Conclusion ......................................................................................................................................... 15

1.4 Materials ................................................................................................................................................ 16

1.4.1 The considered materials ............................................................................................................... 16

1.4.2 How to use the materials ................................................................................................................. 17

1.4.3 Recommendation ............................................................................................................................. 19

2. Stability ...................................................................................................................................................... 20

2.1 Static stability .......................................................................................................................................... 20

2.1.1 Conclusion .......................................................................................................................................... 23

2.2 Inclination test .......................................................................................................................................... 24

2.2.1 Conclusion .......................................................................................................................................... 25

2.3 Dynamic stability .................................................................................................................................... 26

2.3.1 Dynamic stability calculations ......................................................................................................... 26

3. Automation ................................................................................................................................................ 27
3.1 The automating system ........................................................................................................ 27
3.2 The components in the system ........................................................................................ 27
3.3 Extra security ..................................................................................................................... 28
3.4 Keeping the tanks in position ............................................................................................ 29
3.5 How will the tanks be moved? .......................................................................................... 30
   3.5.1 How the computer knows when to move a tank ....................................................... 30
3.6 Conclusion .......................................................................................................................... 30
4. Advantages and disadvantages ......................................................................................... 31
   4.1 Automatic systems ......................................................................................................... 31
   4.2 Materials ........................................................................................................................ 31
   4.3 Hydrodynamics .............................................................................................................. 31
   4.4 Stability .......................................................................................................................... 31
   4.5 Room for cargo/ bunkers .............................................................................................. 31
   4.6 Conclusion ..................................................................................................................... 32
5. Final Conclusion .................................................................................................................. 33
   5.1 Design ............................................................................................................................. 33
   5.2 Materials ........................................................................................................................ 33
   5.3 Stability .......................................................................................................................... 33
   5.4 Automation ..................................................................................................................... 34
   5.5 Advantages and disadvantages ..................................................................................... 34
   5.6 Conclusion ..................................................................................................................... 34
6. Recommendations ............................................................................................................... 35
References ..................................................................................................................................
Preface

The reason this report has been made, is because our school hosts the annual Maritime Symposium. Students of the Rotterdam Mainport University are given a chance to present an new and innovative idea to people of the Maritime industry to help solve problems.

We, project group 7, consist of 5 members. We chose this subject because we thought it was challenging and fun to do. Also, it was much more interesting than the other subjects we could choose from. Our knowledge about this subject was also much greater than other ones.

We would like to thank Mrs Van der Valk for her support and knowledge, Mr Van Kluijven for his supportive character and knowledge too.

A big thanks to Rien de Meij and Jaap van Heerd from MARIN. They helped us very much and gave new insight to our research. Also a big thank you for the interesting tour at MARIN.

Best regards,

Project group 7
Charlotte, Silvio, Sander, Mike and Tim
**Introduction**

Invasive marine species are carried to different parts of the world by ships’ ballast tanks; this often causes harm to regional marine species. This is irreversible, which makes finding a solution to sail without ballast water an important job.

**The main objective**

The main objective is to design a ship which is able to sail without the need of using of ballast water. The absence of ballast water will be compensated by using an upthrusting force of air.

**Main- and sub questions**

*Main question*

How can a ship sail efficiently and safely without ballast water using upthrusting air?

*Sub questions*

1. What design should a ship have to achieve an air ballasted voyage?
2. What are the advantages and disadvantages of using upthrusting air compared to using ballast water?
3. How will the design affect the ship’s dynamic and static stability?
4. How can the upthrusting air system be used automatically?

**Project borders**

In this project we will only research the questions mentioned in the main and sub questions. We will not concern ourselves about the costs that the systems bring with them. Also, the manoeuvrability of a vessel with an upthrusting air system won’t be researched. And we will not research how the ship will react due to heavy weather. We will concern ourselves with the possibility to stabilize a vessel with air instead of water. The possibility of sailing without upthrusting air is described in this report, and a recommendation and conclusion has been made based on the findings.

**Research methodology**

To create the report, we use the knowledge we gained during our time attending the lessons at school, with the help and knowledge of our principal. Those results will be processed on both quantitative and qualitative ways, depending on the part of the investigation. We will do the following:

**Desk and field research**

Desk research: This is the theoretical phase; we found information about the problem. For our desk research we did literature studies, theories, and a problem analysis.

Field research: The field research consists a test with a small scale model of the designed ship and an interview with an expert.
1. The design

1.1 Ballast water

To find out why ballast water is going to be replaced, one needs to know what ballast water is. Ballast water is used nowadays in vessels to improve draft and manoeuvrability when the vessel is not loaded. An increase of draft is desired because the ship’s propeller and rudder are not efficient when the ship has a small draft. This increase in draft results in a better manoeuvrability.

Ballast is also used when the ship is loaded and her stability is not sufficient enough. In this case, ballast water is pumped in the ship at a very low pace. By doing this it will lower the ships centre of gravity. This results in a greater stability, because the distance between the metacentre and the centre of gravity is bigger. When all of the cargo is placed in the middle of the ship, the hull of the ship will receive a huge amount of bending moments and shear forces – a high tension and pressure. By placing ballast water in the fore- and aft tank these bending moments and shear forces are will decrease.

When ballast water is placed in for example, the fore- or aft tank, it is also possible to adjust the trim of the vessel. If there is more water and cargo at the stern of the vessel, she will lay deeper on the stern than on the head. (Ballastwater, 2013)

The topics that will be discussed in this chapter will be :
- 1.1 Ballast water
- 1.2 Concepts
- 1.3 Upthrusting force
- 1.4 Materials

To answer this sub question the following methodologies were used:
- Problem A
- Field research

The kind of water that is used for this is seawater. Annually, over 10 billion tons of ballast water is transported worldwide. Ballast water is loaded in the vessel in tanks, somewhere on the world. When the ballast water is not needed anymore, it is discharged in another place.

Loading and discharging ballast water

For example, the MS STC-Rotterdam is at anchor in the port of Sydney, she needs to discharge her ballast water which she loaded in the port of Lisbon.

In picture 1.1, the top-left ship is loading ballast water in Lisbon (1), while discharging cargo. During voyage to Sydney, the cargo holds are empty but the ballast tanks are full (2). When arrived at Sydney, cargo will be loaded and ballast water is discharged (3). When she sails back to Lisbon with a full cargo hold, the ballast tanks are empty again (4).

Stability

“Stability is the ability of a totally or partially submerged body to float upright, and when forced from the upright position to come back to the upright position when the reason for the list no longer exists.” (Dokkum van, 2008)

When a ship is empty, the Gravitation (G) point of the vessel lies higher, near the metacentre (M). This results in a smaller stability. When the vessel is ballasted the Gravitation point of the vessel goes down. The distance between M and G is increased, resulting in a more positive stability. The ballast water has to be under the Gravitation point, only then the ballast water is useful to lower the Gravitation point. Adding ballast water to the tanks will result in an increase of the draft. Because the volume under the waterline is increased, the centre of buoyancy will rise and will form a new moment with the centre of gravity.

Figure 1.1: Loading and discharging ballast water (Preventing Ballast Water Invasive Species Propagation, 2013)
**Downside**

One huge downside to ballast water is that it is very harmful to the environment. The water contains shellfish, fish, algae, microorganisms such as viruses and other organisms. These normally live in their own water, but suddenly they are scooped up and placed somewhere far away. Their natural living conditions are changed and when those are positive changes, for example: No natural predators hunting them, they can multiply and suffocate the already existing biotope1. When the newly stationed organisms live in their new home, they can harm other animals and humans. Diseases like cholera can be brought over.

Ballast water is also very expensive to sail around the world because ballast water is extra weight that has to be carried from A to B, resulting in higher fuel costs.

Another downside to ballast water is that the ballast tanks are best used when full or empty, or else you will experience a free surface moment which will result in an extending swing each time your ship will roll.

**The IMO**

The International Maritime Organization came up with the Ballast Water Management plan (BWM). This plan came into force in 2004. They mention guidelines and rules which help stop the worldwide problem regarding the discharging of ballast water containing invasive species. Guidelines like: using ballast water treatment methods and the ballast water record book. One important rule is that you cannot discharge untreated ballast water in harbours anymore. (Ballast Water Management, N.D.).

**Air**

Nowadays, the rules are changed in a way that the environment is spared as much as possible. Why not make the vessel (looking at ballast water) itself more environmentally friendly? The possibility of sailing without ballast water but instead with a reversed system based on air is being researched in this report. The idea is to push the ship up to her mark with air. The plimsoll mark is, when the ship is loaded, under water. That is because the ship will be deeper in the water than normal vessels. The systems will, when engaged, lower the floatation tanks and bring her up to her mark. So why choose air? Because it is a passive solution for the ballast water problem. There is no more need for ballast water, because the air replaced it using another method for lifting the ship up using air instead of using ballast water to bring the ship down.

Three concepts, which are described more detailed further in this report, are being compared. Those are:

- **1.2.1 Separate floatation tanks**
- **1.2.2 Large floatation tanks**
- **1.2.3 Compression units**

1 Biotope is an area of uniform environmental conditions providing a living place for a specific assemblage of plants and animals.
1.2 Concepts
The main objective is to design a ship that is able to sail without the use of ballast water. The ship will not have any type of ballast water tanks, and will compensate the absence of the ballast tanks with a bigger weight and an upthrusting force of air. To achieve an air ballasted voyage, a few concepts have been made. When making these concepts they were designed for modern merchant vessels. The type of vessel which is displayed in the images is a general cargo ship. No design concepts were made for other types of vessels. The 3 concepts are:

1.2.1 Separate floatation tanks
This design consists of five floatation tanks attached to each side of the ship, like you can see in figure 1.2, a total of ten tanks. The tanks which are shown in the images are 2 metres wide, 7 metres deep and are 20 metres long. This means it has a displacement of 175 tons resulting into a maximum upthrusting force of 175*1.025 tons minus the weight of the air and the weight of the floatation tank itself.

1.2.1.1 Tank moving mechanism
Each floatation tank can be moved separately in a different vertical position, depending on the vessels loading condition. Each tank is attached on two rails which are integrated in the hull of the ship. The tanks can be raised or lowered using a gear construction or hydraulics. To secure the tank and to ease the stresses on the gear mechanism during the voyage, the rails contains holes every 20 cm, so a heavy pin fuse can be put in these holes to hold the rail and therefore the tank in position. This is to transfer the vertical forces from the tank to the ship, and not to the gear or the hydraulic construction. It has been decided to choose for a hole every 20 cm because considering the size and the effects that these tanks provides, a more precise controlling of this tanks will not make any significant difference in the ballast state of the vessel.

Figure 1.3 shows a close up of one tank. These tanks will inevitably give a ship a larger breadth. The small tanks are the best option to deepen the research in. This is because the following advantages are better than those in the other ideas.

These side tanks can provide a very accurate trim; when there are three or five side tanks on one side of the ship (1 in front, 1 in the middle, 1 on the back) it is possible to bring the aft tank fully down into the water, while the front tank isn’t fully underwater. Thus it has more upthrusting force at the aft of the vessel then at the front.

These tanks will be made of a very strong carbon based material. It will also be lightweight. This is because steel is too heavy. With less weight of the tanks, the tank can deliver more upthrusting force. The heavier the tanks, the less upthrusting force the air in the tanks can deliver. The one eliminates the other.

The ships stability will be increased because of the increased breadth of the ship when the floatation tanks are semi submerged (see chapter 2).
1.2.2 Large floatation tanks
In this design, one large floatation tank is attached to each side of the ship. Each floatation tank has a length of 75 metres, a width of 10 metres and it has a depth of 5 metres. The tanks have a hydrodynamic shape to reduce water resistance. The tanks have a total displacement of 2588 tons, resulting in a buoyancy force of about 2588 * 1.025 =2653. This is without the weight of the tanks. The positions of the two tanks can be set individually. This is done by controlling the 5 rails which are again integrated in the ship's hull. Information on how this works, see: 1.2.1.1.

To control the trim or the ship, these two tanks have an additional feature, the tanks are able to trim 5° forwards or backwards. This is necessary because this would be the only way of controlling the ships trim. By trimming the tank, the bow of the tank will increase or decrease and the aft of the tank will decrease or increase. The forces created by doing this will counter trim the vessel. When the most forward rail is in its lowest position the most backward one is almost in its most upper position, the tank will have a trim of and still have a little room to increase or decrease the underwater volume. However, this does result in a small trimming capability, because he cannot prevent the ship from further trimming when it gains its maximum of 5°.

The disadvantage of this system is that it caused great forces on the rotation point. The rotation point set in the middle of the tank because on that point the tank rotates with less force than in any other position. When the tank rotates, all longitudinal forces will come together in that rotation point. This point has a great amount of forces to bear, so this will be a weak point.

Because of the size of these floatation tanks, the amount of buoyancy will be the largest compared to the other 2 concepts.
1.2.2.1 Explaining the first 2 concepts

To get some understanding in how the first 2 concepts work, they will be explained in a simple way:

When the vessel is equally loaded or discharged she needs to be on her mark. To ensure she is on her mark, the floatation tanks will be brought down, so they can pull the vessel up. The amount of tanks and how far that they will go down is different every time, because the vessel sometimes needs more upthrusting force, for example when having cargo on board. When the vessel needs more buoyancy, the system will react and give her the amount she needs.

When the vessel is loaded with a different weight of cargo on each side, the tanks at the side of the cargo will go down, the ones at the other side stay up, but when necessary they can be brought down just to increase the area water line.
1.2.3 Compression units.

This system is comparable to the current system where ballast water is stored in ballast tanks. In this new system, there are two long horizontal funnels through the bottom of the ship. (Figure 1.9) When the ship is not loaded these tunnels are open and they are filled with water. If extra buoyancy is required, the Compression units can be pushed down in order to lessen the draft. The size of the blocks are: 5 metres long, 8 feet wide and 3 feet deep.

Each block can be adjusted individually which will allow an ideal situation for the ships loading condition. (Figure 1.8)

A block is moved by four hydraulic cylinders; these push the block against the hydropower in the tunnel and ‘squeeze’ the water out of the funnel to create the air in the funnel. To prevent longitudinal forces on the cylinders, each block has a guide rail in the tunnel in which all the longitudinal forces can transferred to the ship.

To ensure that there is no water above the blocks, each one is and sealed with a rubber. Furthermore, the space above the press blocks has an overpressure in order to prevent any inward leakage. To avoid stagnant water in the tunnel (something that could happen when the ship is in a hogging situation, when at both ends of the ship the blocks are lowered) the blocks are always 95% closed so there is always some flow is for flushing organisms away.

This system will cause a ship to have a larger draft. The ship’s draft would be larger due to the storage of the blocks.

Adding air to the keel of the ship will also cause the ship to have less dynamic stability. This will be a big disadvantage to this concept.
The advantages and disadvantages of every concept

In table 1.10 the properties of each concept can be found. The advantages and disadvantages can be derived from this table.

Table 1.10

<table>
<thead>
<tr>
<th>Type of concept</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2.1 Separate floatation tanks</td>
<td>Stability: (+) Stability is increased: when calculating the stability, the breadth is powered to the third. So when the tanks are in the water the stability increases, even with a relatively small increase of the width of the vessel.</td>
</tr>
<tr>
<td>1.2.2 Large floatation tanks</td>
<td>(+) Great stability: The moulded breadth is increased due to the tanks on both sides, which causes more stability.</td>
</tr>
<tr>
<td>1.2.3 Compression units</td>
<td>(-) Less stability: Adding air to the keel of the ship causes less (dynamic) stability.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability</td>
</tr>
<tr>
<td>Trim</td>
</tr>
<tr>
<td>Breadth</td>
</tr>
</tbody>
</table>

(-) bad  (-) poor  (+-) average  (+) good  (+++) Very good

**Stability**

- (+) Stability is increased: when calculating the stability, the breadth is powered to the third. So when the tanks are in the water the stability increases, even with a relatively small increase of the width of the vessel.

- (+) Great stability: The moulded breadth is increased due to the tanks on both sides, which causes more stability.

- (-) Less stability: Adding air to the keel of the ship causes less (dynamic) stability.

**Trim**

- (+) Very accurate trim: when you have three or five side tanks on one side of the ship (1 in front, 1 in the middle, 1 on the back) it is possible to bring the aft tank fully down into the water, while the front tank isn’t fully underwater. Thus it has more upthrusting force at the aft of the vessel then at the front.

- (+) Not such accurate trim: One big tank cannot be trimmed as well as three smaller tanks. The trim is harder to control which could result to less maneuverability. The tanks can only be “counter-trimmed” as much as 5 degrees down on the stern or bow.

- (+) Accurate trim: The trim can be adjusted easily. Each block can be adjusted individually which will allow an ideal situation for the ships loading condition.

**Breadth**

- (-) Increased breadth: A vessel with side tanks will have a bigger moulded breadth than a vessel without side tanks.

- (-) Breadth increased because of the floatation tanks to the sides.

- (+) No increased breadth: The ship’s moulded breadth would not have to be increased. In contrary to the other concepts.
<table>
<thead>
<tr>
<th>Type of concept</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2.1 Separate floatation tanks</td>
<td>1.2.2 Large floatation tanks</td>
</tr>
</tbody>
</table>

| Draft | (+) No increased draft | (+) No increased draft | (-) A larger draft: The ships draft would be larger due to the storage of the blocks, when a larger draft is created it might be possible that the vessel cannot sail everywhere. |
| Amount of upthrusting force | (+) Medium upthrusting force, depending on the size of the tanks. The amount of upthrusting force will be less than the idea with 2 large floatation tanks, this is because these floatation tanks are smaller. | (+) Great upthrusting force: It has the largest amount of upthrusting force because of its enormous under water volume | (+) Medium upthrusting force: The amount of upthrusting force is limited because of the size of the funnel in the ship. |
| Berthing | (-) Berthing: with the side tanks it will be more difficult to berth because the tanks won't be easy to see from the bridge. The vessel will be further away from the side, and might even be too far for the facilities at shore to reach the vessel, for example a container crane. | (-) Berthing: with the side tanks it will be more difficult to berth for the same reasons as the concept with the separate floatation tanks. | (+) Berthing: The fact that this system does not have an increased breadth will be a big advantage when berthing compared to the other 2 concepts (it will not need special container cranes). |
| Forces | (+) To secure the tank and to ease the stresses on the gear mechanism during the voyage, the rails contains holes every 20 cm, so a heavy pin fuse can be put in these holes to hold the rail and therefore the tank in position. | (-) Rotation point: the rotation point is chosen to be in the middle of the tank because there the tank rotates with less force the than in any other position. When the tank rotates, all longitudinal forces are coming together in that rotation point, this point has a great amount of forces to bear. | (+) To prevent longitudinal forces on the cylinders, each block has a guide rail in the tunnel in which all the longitudinal forces can transferred to the ship. |

(Dokkum van, 2008)
1.2.4 Conclusion

After looking carefully at the advantages and disadvantages of the 3 concepts, the separate floatation tanks has chosen to be the best idea, and therefore the rest of the research will be directed to that idea.

Compression units

The idea of the compression units was ruled out because it would decrease the stability of the ship, so the ship would not be able to sail safely. The fact that the stability of the ship would decrease a lot, was a major issue and therefore this idea was ruled out first.

Large floatation tanks

The idea with the 2 large floatation tanks will not be researched in this report because there are concerns about the extreme forces in the rotation point; this rotation point (in the middle of the tank) has to take on great forces when the ship has a trim. This might give problems during voyage and therefore the system with smaller floatation tanks was a better option.

Separate floatation tanks

With several floatation tanks the trim of the vessel can be made very accurate but also maintain a certain amount of stability and maneuverability. The trim could be controlled most accurately comparing to the other two systems. The increased stability, the accurate trim, and the fact that the forces on these tanks will be divided between these tanks were the most important reasons to pick this concept for further research.
1.4 Materials
To realize a ship that can sail without the use of ballast water, materials that can carry the air within the tanks but also are lightweight have to be used. They must not break, rust and have to withstand great forces. Instead of traditional, obsolete materials like steel, one needs to use newer, stronger ones. Two materials that already have been researched thoroughly for non-maritime purposes may be a solution, polypropylene and graphene.

1.4.1 The considered materials

Polypropylene
Polypropylene is a strong plastic and yet lightweight. It can withstand over 4,000 pounds of pressure per square inch (281.2 kilograms per square centimeters). It replaces many metals as well as concrete. It will not show wear and does not rust or react with water in any way. It also will not react with acid, detergents or non-oxidizing organic compounds. It will last over hundreds of years and is three times stronger than steel. Polypropylene is already used in jerry cans, carpets, plastic furnishing, small sailing yachts and ropes. Polypropylene will float on water so that is a major benefit for the project’s sake (Polypropylene, 2013).

Graphene
This is a carbon based, elastic super thin material, like paper but ten times stronger than steel. It is a single layered area of carbon atoms, like chicken wire. Because it is so thin, it can be used for protective matters but also, when having more layers from it, as a more rigid structure than steel. It is nearly transparent and an excellent conductor of heat and electricity. It has a tensile strength or stiffness of 150 million pounds per square inch (10.5 million kilograms per square centimeters). It also will not wear away like polypropylene. It is incredibly lightweight, six times lighter than steel and nearly 200 times more resistant to breaking than steel. Fortunately, it is not difficult to make. Graphene is used in numerous innovative applications such as in the bio-industry, in the military and as an energy storing material (New Graphene Material is Paper-Thin and Ten Times Stronger Than Steel, 2011).

Steel
Steel is an alloy of iron and a small amount of carbon. Carbon is the primary alloying element, and its content in the steel is between 0.002% and 2.1% by weight. Additional elements may also be present in steel: manganese, phosphorus, sulphur, silicon, and traces of oxygen, nitrogen and aluminium. It is a highly commercialized product and the world’s economics revolve around products like steel. It is a strong material which is not very expensive. Nowadays, steel is used for a bunch of things. It is used as building material, as railroad track, it can be found in guns, in vessels, cars, sport equipment, skyscrapers, and so on (Quak, 2004).
1.4.2 How to use the materials

An idea is to make the air filled “tanks” from either one of these products. The tanks have to be strong and lightweight, because they have to protect the precious air inside that will provide the upthrusting buoyancy force.

Plates

When researching, an article coming from the Dutch Regulations Researching Vessels on the Rhine (ROSR) came up. It describes what plate thickness the steel plates of a vessel's hull need to have to be allowed to sail on the Rhine. It does not only apply for inland shipping, but also for seagoing vessels. Because the regulations apply to seagoing vessels and as a Dutch project (because sailing in Dutch waters will be nice), the ROSR will be the guideline for the calculations regarding plate thickness. (ROSR)

Vessels that have been made from steel have to have a minimal hull (plate) thickness (tmin). The equations in the annexes will help calculating it. When calculating, please note that it has been calculated for the side tanks. The equation for a vessel has been chosen because, the tanks will increase the width, and will carry a reasonably large amount of the vessel’s weight. So, it needs to be as rigid as if it is the normal hull. When trying to calculate the factors and measurements of the vessel’s side tanks, it has been decided to use the frame spacing of the whole ship instead of only one tank. This is because those tanks will be on the outside of the ship. This is like the same reason as before, they have to be as durable as the hull itself. (Black, 2002)

The shape of the side tanks were simplified to a cuboid block. This is to simplify the calculations of the possible weight. The exact shape of the floating tank is too complex to measure.

Steel plates for the side tanks

\[ t_{\text{min}} = f \cdot b \cdot c \cdot (1.5 + 0.06 \cdot L) \]

<table>
<thead>
<tr>
<th>Measurements of 1 tank (of 10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>length</td>
</tr>
<tr>
<td>width</td>
</tr>
<tr>
<td>height or draft</td>
</tr>
<tr>
<td>frame spacing</td>
</tr>
<tr>
<td>volume 1 tank</td>
</tr>
<tr>
<td>density water</td>
</tr>
<tr>
<td>( \Delta ) 1 tank</td>
</tr>
<tr>
<td>( \Delta ) 10 tanks</td>
</tr>
<tr>
<td>Tensile strength steel</td>
</tr>
<tr>
<td>density steel</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bottom and side plates</th>
<th>tmin</th>
</tr>
</thead>
<tbody>
<tr>
<td>tmin</td>
<td>18,495 mm</td>
</tr>
<tr>
<td>f</td>
<td>6.85</td>
</tr>
<tr>
<td>b1</td>
<td>1</td>
</tr>
<tr>
<td>b2</td>
<td>1.25</td>
</tr>
<tr>
<td>c</td>
<td>1</td>
</tr>
<tr>
<td>L</td>
<td>20 m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bottom and side plates</th>
<th>tmin</th>
</tr>
</thead>
<tbody>
<tr>
<td>total volume plates</td>
<td>4,938,042,066 m³</td>
</tr>
<tr>
<td>weight 1 tank</td>
<td>385,167,728,111 kg</td>
</tr>
<tr>
<td></td>
<td>38,52 tons</td>
</tr>
<tr>
<td>weight 10 tanks</td>
<td>385,167,281,111 kg</td>
</tr>
<tr>
<td></td>
<td>385,167,281,111 tons</td>
</tr>
<tr>
<td>buoyant force</td>
<td>1392,951,469 tons</td>
</tr>
</tbody>
</table>

Table 1.1: Calculating steel plate thickness
One steel tank weighs about 38.52 tons. The total weight that is added to the ship from the filled air tanks is 385.16 tons. That is because this concept has ten tanks, five on each side. This is still quite heavy. The upthrusting force or buoyancy that the air-filled tanks can deliver, bearing in mind that the weight of the steel tanks itself is subtracted, is 1393 tons.

**Comparing**

To compare the two materials for a reasonable outcome, the thickness will be the same as a steel hull. This is because polypropylene is stated to be three times stronger than steel, graphene is ten times stronger than steel. So, if that is the case, it should easily withstand as much force as steel.

The only thing that will be calculated is the weight. If it is as strong as steel but much lighter, it has an advantage over it and thus being more useful. When the tanks are lighter, the amount of upthrusting force will be higher, which will result in a higher efficiency of the tanks. And using it will cost less fuel in comparison with steel. The calculations for polypropylene do not differ very much from steel. The only changes, which immediately are the most important changes, are the tensile strength and density. While the tensile strength does not take part in the calculations, it is a key property of those materials. The higher the tensile strength, the more force it can withstand. Density is a key factor in this case, because the lower the density, the lower the weight of the tanks. When the tanks are lightweight, the amount of buoyancy the tanks will deliver will relatively be higher. The maximum amount of buoyant force the tanks can deliver is 1778 tons minus their own weight. (Technical Information and Engineering Properties, N.D.)

**Calculating layers**

Polypropylene is very light, when comparing it with steel. Only 44.8 tons. That is a very positive-looking weight considering that could be the material for the tanks. But graphene is another story. When trying to find a density for graphene, one will not find a unit as the ones for the other two materials. That is because, normally, graphene is used as a one-atom thick surface.

---

### Polypropylene plates for the side tanks

<table>
<thead>
<tr>
<th>Measurements of 1 tank (of 10)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>length</td>
<td>20 m</td>
</tr>
<tr>
<td>width</td>
<td>2 m</td>
</tr>
<tr>
<td>height or draft</td>
<td>7 m</td>
</tr>
<tr>
<td>frame spacing</td>
<td>5000 mm</td>
</tr>
<tr>
<td>volume 1 tank</td>
<td>173,475 m³</td>
</tr>
<tr>
<td>density water</td>
<td>1,025 tons/m³</td>
</tr>
<tr>
<td>Δ 1 tank</td>
<td>177,8119 tons</td>
</tr>
<tr>
<td>Δ 10 tanks</td>
<td>1778,119 tons</td>
</tr>
<tr>
<td>Tensile strength_polypropylene</td>
<td>1068,7 N/mm²</td>
</tr>
<tr>
<td>density_polypropylene</td>
<td>909 kg/m³</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bottom and side plates</th>
<th>tmin</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>tmin</td>
<td>18,495 mm</td>
<td>0,018495 m</td>
</tr>
<tr>
<td>f</td>
<td>6,85 cm</td>
<td></td>
</tr>
<tr>
<td>b1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>b2</td>
<td>1,25</td>
<td></td>
</tr>
<tr>
<td>c</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>20 m</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bottom and side plates</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>total volume plates</td>
<td>4,938042 m³</td>
</tr>
<tr>
<td>weight 1 tank</td>
<td>4488,68 kg</td>
</tr>
<tr>
<td>weight 10 tanks</td>
<td>44886,8 kg</td>
</tr>
<tr>
<td>buoyant force</td>
<td>1733,232 tons</td>
</tr>
</tbody>
</table>

*Table 1.2: Calculating polypropylene plate thickness*
To calculate how much layers of graphene is needed to have a 1.8495 cm thick plate, the radius of one carbon atom needs to be determined. The size of atoms can be estimated with the use of Avogadro’s number along with the atomic mass and bulk density of a solid material. From these, the volume per atom can be determined.

\[
\text{Atomic volume} = \frac{\text{Molar mass (gm)}}{(\text{density in gm/cm}^3) \times (\text{Avogadro's number})}
\]

The cube root of the volume is an estimate of the diameter of the atom. For carbon, the molar mass is exactly 12, and the density is about 2 gm/cm\(^3\). The estimated volume is then:

\[
\text{Carbon atomic volume} \approx \frac{12 \text{ gm}}{(2 \text{ gm/cm}^3) \times (6.02 \times 10^{23})} \approx 9.97 \times 10^{-24} \text{ cm}^3
\]

And the estimate of the carbon atomic diameters is the cube root of that. 

\[
\text{Carbon diameter} \approx 2.2 \times 10^{-8} \text{ cm} = 0.22 \text{ nm}
\]

The atom is 0.22 nm thick. The next step is to figure out how much of those layers fit in 1.8495 cm. The answer to that is 8406818.182 graphene layers.

**1.4.3 Recommendation**

Graphene and polypropylene are the materials that are best suited for the job, while graphene being not as lightweight as polypropylene, it is incredibly strong. Polypropylene is used more often nowadays, so it is less expensive to make. Both of the materials are less heavy than steel, so a vessel can almost use the maximum buoyant force of the tanks. Graphene is very strong, so it can take a hit very well. Polypropylene is strong as well but not in the order of graphene. Both do not rust, nor break which is good for durability issues. To make graphene, you need graphite ore, in large amounts. 40 times more graphite is needed to make graphene. Fortunately, mankind can combine two materials to create a stronger one. The recommendation is as follows, combine the two to create an alloy of graphene and polypropylene or use one of them. Either one is okay, because they are stronger and less heavy than steel.

### Graphene plates for the side tanks

<table>
<thead>
<tr>
<th>Measurements of 1 tank (of 10)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>length</strong></td>
</tr>
<tr>
<td><strong>width</strong></td>
</tr>
<tr>
<td><strong>height or draft</strong></td>
</tr>
<tr>
<td><strong>frame spacing</strong></td>
</tr>
<tr>
<td><strong>volume 1 tank</strong></td>
</tr>
<tr>
<td><strong>density water</strong></td>
</tr>
<tr>
<td>(\Delta 1) tank</td>
</tr>
<tr>
<td>(\Delta 10) tanks</td>
</tr>
<tr>
<td><strong>Tensile strength graphene</strong></td>
</tr>
<tr>
<td><strong>weight graphene</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bottom and side plates</th>
<th>tmin</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>tmin</strong></td>
<td>18,495 mm</td>
</tr>
<tr>
<td><strong>f</strong></td>
<td>6.85 mm</td>
</tr>
<tr>
<td><strong>b1</strong></td>
<td>1 mm</td>
</tr>
<tr>
<td><strong>b2</strong></td>
<td>1,25 mm</td>
</tr>
<tr>
<td><strong>c</strong></td>
<td>1 mm</td>
</tr>
<tr>
<td><strong>L</strong></td>
<td>20 m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bottom and side plates</th>
<th>tmin</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>total surface</strong></td>
<td>266,9933531 m(^2)</td>
</tr>
<tr>
<td><strong>weight tank, 1 layer</strong></td>
<td>2055,85 mg</td>
</tr>
<tr>
<td><strong>layers</strong></td>
<td>8406818,182</td>
</tr>
<tr>
<td><strong>1 tank</strong></td>
<td>17283147230,1 mg</td>
</tr>
<tr>
<td><strong>weight 1 tank</strong></td>
<td>17283,15 kg</td>
</tr>
<tr>
<td><strong>weight 10 tanks</strong></td>
<td>17,283 tons</td>
</tr>
<tr>
<td><strong>buoyant force</strong></td>
<td>1605,287 tons</td>
</tr>
</tbody>
</table>

*Table 1.2: Calculating graphene plate thickness*
2. Stability

Ship stability is one of the most important factors in sailing safely. “Stability is the ability of a totally or partially submerged body to float upright, and when forced from the upright position to come back to the upright position when the reason for the list no longer exists” (Dokkum van, 2008)

Stability depends on the shape of the vessel, the weight of the vessel and cargo. The stability of a ship has to be calculated before departure, it is required by law to calculate it. This is because a too small stability can lead to capsizing of the ship.

When a compartment in a ship is being ballasted, the air in that compartment is filled with heavy fluids. The buoyant force provided by the compartment is then compensated by the moved centre of gravity. Vice versa, when using the tanks, the moment they touch the water they add extra buoyancy, which will be in our advantage. For this project calculations on ship stability have been made to be able to determine if the concept works, and if not, how it can be improved. The topics that will be discussed in this chapter will be:

- 2.1 Calculation of the static stability
- 2.2 Calculation of the dynamic stability
- 2.3 Conclusion

To answer this sub question the following methodologies were used:
- Desk research
- Field research

2.1 Static stability

A ship’s static stability is calculated with the ship’s hydrostatic data. This means that the calculations of static stability are made for a situation when a ship is not moving.

For calculating the ships static stability the measurements of the barge have been taken, this to simplify the calculations. The breadth of the ship is 27 metres, and the length is 170 metres. The ships stability is calculated for a draft ranging from 0.1 to 8 metres with an interval of 0.1 metres.

In the spread sheet in Annex 1 the static stability calculations can be found.

To help understand what the different terms for the stability calculations are, an explanation is given:

The metacentre, centre of gravity, centre of buoyancy and keel are imaginary points in the ship.

\[ M \] stands for metacentre and this is, when the ship is inclined while having a maximum list of 5 degrees, the point in which the lines of buoyant forces intersect. As the ship is inclined, the centre of buoyancy will move in an arc to seek the geometric centre of the underwater hull body.

\[ G \] stands for centre of gravity. This is the point at which all of the gravitational forces come together. The position of \( G \) depends on the distribution of mass within the vessel. If cargo is being moved within the ship, \( G \) acts as follows: A weight addition will attract \( G \) to the added weight.

When removing weight, \( G \) moves away from the removed weight. When shifting weight, \( G \) will move in the same direction as the shifted weight.

\[ B \] stands for centre of buoyancy. This is the geometric centre of the vessel’s underwater hull body. All the forces of buoyancy will come together in this point in a vertically upward direction.

\[ K \] stands for keel and this is the bottom of the ship. It is the point of which all the forces of buoyancy will move in an upward direction. (Dokkum van, 2008)
The letters can be combined to form distances from each another. KM is the Keel – Metacentre distance and this is used in stability calculations. MB is the metacentric radius, the distance between the centre of buoyancy and the metacentre. It is the radius of the circle for the movements of B at small angles of heel. The Area Water Line or AWL is the area that the ship takes in from the water surrounding it. The displacement is the volume under the AWL that the ship moves away in the form of water. The Ix value is the transversal moment of inertia of the waterline area, its value will indicate how much resistance a body gives to a change of turning speed with a particular mass.

The KM value has been calculated for different positions of the floatation tanks, and various drafts. These calculations can be found in annex 5.

To be able to see the relation between the different positions of the floatation tanks, the draft, and loading conditions, several calculations were made:

1. **AWL (Area Water Line)**

   For calculating the AWL, normally the trapezium rule is used:
   
   \[ Awl = dx \times ((0.5 \times y_0) + y_1 + y_2 + \ldots + y_6 + y_7 \times 0.5) \]

   Since the measurements of a barge have been taken, calculating the AWL when the tanks are not in the water is quite easy.
   
   \[ AWL = lb \]
   \[ AWL = 170 \times 27 = 4590 \text{ m}^2 \]

   The AWL can also be calculated for when the floating tanks are in the water.
   
   \[ AWL_{\text{including floatation tanks}} = (L_{\text{ship}} \times B_{\text{ship}}) + (L_{\text{fl. tanks}} \times B_{\text{fl. tanks}} \times \text{Number of tanks}) \]

   For example:
   \[ AWL = (170 \times 27) + (10 \times 20 \times 2) = 4990 \text{ m}^2 \]

2. **The ship’s underwater volume (displacement)**

   The next step is to determine the ships underwater volume. This can be done by multiplying the AWL with the ships draft. This can only be done when the ships underwater volume is rectangular. If not, the trapezium rule has to be used.

   For example:
   \[ Volume = AWL \times Draft = 4990 \text{ m} \times 5 \text{ m} = 24750 \text{ m}^3 \]
3. Distance between Keel and centre of Buoyancy

The amount of upthrusting force depends on the volume of the ship’s underwater body and density of the water. When calculating the centre of buoyancy, the ship had a block coefficient of one. So, its shape is a block. Theoretically, the centre of buoyancy is at half the volume of the submerged part of the ship when it is block shaped. The height of the point of buoyancy (KB) for a normal ship can be found for each draft in its hydrostatic table.

For example:
When a rectangular shaped barge has a draft of 5 metres, the point of buoyancy will be at 2.5 metres measured from the keel.

4. Ix

In order to be able to calculate the distance buoyancy- metacentre, the Ix value needs to be determined. The Ix value is the transversal moment of inertia of the waterline area. For a rectangular shaped vessel Ix can be calculated with the following formula:

\[ I_x = \frac{1}{12} \times l \times b^3 \]

In this formula L is the length of the submerged part of the ship, B is the breadth of the submerged part is the ship. (Traagheidsmoment, 2013)

For example:
\[ I_x = \left(\frac{1}{12}\right) \times 170 \times (4590/170)^3 \]
\[ I_x = 278842.5 \]

5. Distance Buoyancy - Metacentre

The height of the ship’s metacentre is important in calculating a ships initial stability. The metacentre point M is the point at which the ship is virtually suspended. The distance buoyancy-metacentre can be calculated with the following formula:

\[ BM = \frac{I_x}{V} \]

For example:
\[ BM = \frac{278842.5}{22950} = 12.15 \text{ m} \]

From this formula it can be derived that when the breadth of the ship is enlarged, and the ship’s underwater volume does not change significantly, the height Buoyancy- metacentre increases quite a lot. This means that when only a small part of the floatation tanks are submerged, the distance between buoyancy and metacentre is at a maximum, and therefore the total height of the metacentre is increased. When the floatation tanks are fully submerged the KM (distance keel metacentre) is at its minimum. This means that when the floatation tanks are gradually lowered in the water, the MB decreases until the tanks are completely submerged.
2.1.1 Conclusion
From the calculations made in this chapter several conclusions can be made.

- The upthrusting force will increase when the floating tanks are in the water. The graphs in annex 4, and the calculations in annex 5 will help visualize the calculations.

- The AWL (Area Water Line) will increase when the tanks are touching the water. This is because the tanks are not submerged. When these tanks are submerged for a relatively small part, almost no extra volume is added under water. Only the AWL is slightly being enlarged, assuming that the sea is calm.

- This increase of the AWL increases the height of the metacentre, even when the volume only slightly increases.

- The height of the ship’s KB (Keel – Buoyancy distance) will be lower when the floating tanks are in the water.

- The MB (Metacentre – Buoyancy distance) will increase when the tanks are touching the water, it will decrease again as soon as they are fully submerged.

- The ship’s KM (Keel – Metacentre distance) is higher when the floating tanks are in the water, but this extra gained stability disappears immediately when the tanks are fully submerged.

- In short this information provides two possibilities: Either the ship acquires extra volume by almost submerging the tanks, or there is the possibility to go for maximum stability by making the tanks just touch the water, with a little as possible volume.
2.2 Inclination test

One of the laws state that every seaworthy ship on open water should have a GM of at least 15 CM. This gives a good picture of the stability that the vessel has at that moment. To determine the GM, an inclination test has been done on a small scale model of the ship, on which calculation have been made. By doing this test it can be determined if the tanks give a desired extra GM. An inclination test can be done by moving weights transversely, which will result in a overturning moment. When several dimensions are known, the GM can be calculated.

To do the test, a rectangular cube-shaped Styrofoam model of the ship has been made. The floating tanks have also been made from Styrofoam. A lightweight plummet was hung on a stick attached to a thin tread, which would act as the clinometer of the ship. First, the test was ran without the floating tanks, which would act as if the tanks were out of the water, or "up". When the vessel was in the water and on brought to the desired depth by ballast. The inclining test began by shifting 1% of the total weight of the vessel in a transversely direction to the side of the vessel. By doing this there has formed an incline of about 4”, this incline is the result of the stability. When that was finished, the model was taken out of the water and prepared for its next test, the tanks semi-submerged. The tanks were attached to the ship with two nails, not fully piercing the model’s hull. The test was ran again and also a third time with the tanks fully submerged. All times the distance of the shifted weight and the angle of incline was measured. (Ferreiro, 2006)

To make sure the test results were reliable, the test was done in still water so there were no influences of waves and wind. The shape that was used to perform the test was the shape of the calculations, this means that it has a block coefficient of 1.

The formula used to determine the height of the metacentre is:

\[ GM = \frac{p \times a}{\Delta} \times \frac{l}{u} \]

In this formula the dimensions are:

- \( p \) = the weight that was shifted
- \( a \) = the distance of the displacement
- \( l \) = length of the plummet
- \( u \) = the difference in transversal displacement
- \( \Delta \) = the amount of water that the vessel displaces, expressed in metric tonnes.
- \( GM \) = The distance between the centre of gravity and the metacentre

Our model has a scale of 1:200 so the measurements of our model are 85x13.5x4.3 cm. The size of the floatation tanks are: 10x1x3.5 cm. Figure 2.3 shows an AutoCAD picture of the Styrofoam model. The weight of the ship was measured and its weight was 128 gram (including floating tanks excluding ballast and 3500 gram including ballast).

To make good use of the provided formula, the ship’s displacement needs to be calculated. The density of the water was 1000 kg/ m³, so the ship’s displacement is also 128 gram(including floating tanks, excluding ballast and 3500 gram including ballast).

To achieve an accurate GM value the weights that will be shifted should be no more than 1 % of the ship’s displacement. The weights that were used had a weight of 0.035 kilogram. The distance between the centre line and its eventual position was 5.8 cm.

Figure 2.3: Scale model in AutoCAD
The measured values after the inclining tests were:

<table>
<thead>
<tr>
<th>Position of floatation tanks:</th>
<th>Floatation tanks up</th>
<th>Floatation tanks semi submerged</th>
<th>Floatation tanks submerged</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>0.035</td>
<td>0.035</td>
<td>0.035</td>
</tr>
<tr>
<td>A</td>
<td>0.058</td>
<td>0.058</td>
<td>0.058</td>
</tr>
<tr>
<td>Δ</td>
<td>3.4425</td>
<td>3.4425</td>
<td>3.4425</td>
</tr>
<tr>
<td>L</td>
<td>0.40</td>
<td>0.40</td>
<td>0.40</td>
</tr>
<tr>
<td>U</td>
<td>0.9*10^{-2}</td>
<td>0.8*10^{-2}</td>
<td>1.8*10^{-2}</td>
</tr>
<tr>
<td>GM =</td>
<td>0.02621 m</td>
<td>0.02948 m</td>
<td>0.01310 m</td>
</tr>
</tbody>
</table>

The GM values are shown in graph 3.1. As graph 3.1 shows, the GM is at its highest when the floatation tanks are semi submerged, and at its lowest when they are fully submerged. This corresponds with the calculations for static stability in the previous paragraph. Usually to perform a reliable inclining test, larger scale models are produced. So this test will only show the relation between the GM value and the position of the floatation tanks.

Graph 3.1

2.2.1 Conclusion
The main aim of this experiment was to see if the tanks have the desired and the same result as calculated in the previous chapter. From graph 3.1 it can be concluded that the ship’s stability is at its highest when the floatation tanks are semi submerged. The ship’s stability is lowest when the floatation tanks are fully submerged. This corresponds with the static stability calculations in the previous chapter. From this it can be derived that the GM decreases rapidly when the floatation tanks are fully submerged, therefore when much stability is required it is recommended that the floatation tanks will not be completely submerged.
2.3 Dynamic stability

When a ship floats upright, the centre of gravity and buoyancy are on the centreline. The resultant force acting on the ship is zero, and the resultant moment about the centre of gravity is zero. But, now a couple of tanks are attached to the ship. They will have their own MB, KG and KB. When the tanks are moved vertically and one of them touches the water, the centre of buoyancy and gravity will change position and thus the resultant moment will change. External forces (wind and waves) during voyage will cause a ship to list.

2.3.1 Dynamic stability calculations

To be able to calculate the dynamic stability of the ship, the same measurements and data should have been taken from the static stability calculations. To determine the stability of the vessel, the GZ or lever of stability was determined. The lever of stability can be calculated for different angles of list, and with these data a ship's stability curve can be made. The lever of stability is the ability of a ship to float upright. The equation for this is:

$$GZ = NK \sin \varphi - GK \sin \varphi.$$  

The N in this formula is called the false metacentre. For small angles (up to approximately 6 °) the metacentre value (calculated in the static stability calculations) can be used for a reliable calculation of the stability lever. The NK value is usually given by the ship builder and is given in a graph with the displacement on the X axes and the NK value on the Y axes. There are usually different curves which represent the different angles of heel (usually with an interval of 5 °) (Derrett, 2006), (Metzlar, 1990).

Because it is quite difficult to calculate the NK distance, it has been assumed that the NK distance is the same as the MK distance. In reality the point M will spiral away from amidships line, and because of this the values will become inaccurate and will only be representative for small angles of list. Calculations were done to determine (approximately) the real data, but this was too far-fetched with our knowledge. Therefore the calculations are left out of the main report.

In reality the stability curve will be bumpy because of the floatation tanks attached to the sides. When they hit the water or get submerged this will give a sudden increase or decrease in the stability of the vessel.

Conclusion

From all successful calculations in this and previous chapters it can be deduced that the initial stability is higher when the floatation tanks are semi-submerged, which corresponds with the static stability calculations and the inclining test. Although a complete calculation on this matter is too far-fetched for our knowledge, it would be possible for an expert on ship building to make these calculations, and thus it might provide significant information in further research for this project.
3. Automation

The system needs to be controlled automatically because it is more accurate and saves a lot of time. The system will be initiated after permission is given by an officer, therefore the system will be protected by, for example, a password. The officer can shut down the system because, for example, when the ship is in dock the system wouldn’t understand the situation.

The whole system consists of the following parts: a draft measurement system; a central controlling system and an operating system. The whole system can be put in an small and organized plan with three main organs: the controlling organ; the correcting organ and the measuring organ (see fig. 1 for the plan).

3.1 The automating system

The controlling instrument consists of three major components: the input, the comparison element and the control element. The input is a panel where the officer inserts the required draft. This is the comparing element, this is where the input signal and the signal from the pressure transmitter are being compared. The discrepancy is send to the controlling element, this element converts the difference into digits which the operating element can understand.

The operating element forms together with the correcting element the correcting organ. The operating element checks the measured values and sends out a signal to the correcting element to start or stop the engines. The engines will move the tanks vertically up or down. Figure 3.1 shows a block schedule of the process. Additionally an extra security system was added in which the computer verifies the moving of the tanks (see part extra security and fig. 3.3).

The height of the tanks will affect the draft of the ship, this will also affect the pressure on the pressure transmitters. The transmitter send the new signal to the comparison element and the circuit is complete and starts again. (Breimer, 2003)

3.2 The components in the system

- The input can simple be a small touchscreen panel or a program running on a computer or even the loading computer (see fig. 3.2 for touchscreen).
- The comparison element, the control element and the operating element are together built in a single computer, perhaps the loading computer.
- The correcting element in this case, are the engines which make the tanks move up and down. These engines will receive an electric signal from the operating element. The engines can be operated separately by the computer.
- The tanks moving up and down is the process, how the tanks look like is described above in the part concepts (page 12) and materials (16).
- The transmitter is a pressure transmitter (see fig 3.3), it will convert the pressure, due to the height of the seawater, into an electric 4-20mA signal which is transmit to the connection box. This box transmits the signal to the comparison element. There will be six transmitters placed around the ship (see fig. 3.4).

**3.3 Extra security**

The extra security is a height transmitter (see fig. 5) The computer sends a signal to the engines. When the tanks are moving the height transmitter transmits a signal to the loading computer. The computer receives the signal and when the signal does not change an alarm will set of an the engines will be stopped. Because when the signal does not change the tanks aren’t moving, this will lead to damage to the tanks and engines.

For the measurement instruments, the draught measurement systems from Hoppe-marine and Barksdale can be used (Draught measuring system, N.D.), (Youtube, N.D.).

**Advantages:**
- When using “live zero” a broken component will be noticed quick because it will be 0 mA instead of 4 mA, this saves time when it is broke.
- When the system works properly a lot of time is saved, because the system will run, control and checks itself, this makes any extra work for the crew otiose.

**Disadvantages:**
- Because the electrical wires are so long, the length of the ship, there can appear problems with the resistance of the wires when they are warming up and cooling down. Because the wires are long potential problems won’t be easy to fix.
3.4 Keeping the tanks in position

When the tanks are under water there will be an enormous force working upwards. The engines which push the tanks down are working very hard to keep the tanks under water. To stop the engines there will be multiple pins holding the tanks in position. The electric system will look like the figure 6. The computer will receive an electric signal from the safety pin system, this signal will be simple “yes” or “no”. This means the pin can be locked or not, when the signal is “no” the computer will order the engine to keep moving. When the signal is “yes” the computer demands the engine to stop. When the engine is stopped the pin can be locked, this is done in a hydraulic system (see fig. 3.7 for not locked and fig. 3.8 for locked).

Fig. 3.6 Electric safety pin system

Fig. 3.7 this is how the hydraulic system looks when the pin is not locked

Fig. 3.8 this is how the hydraulic system looks when the pin is locked
3.5 How will the tanks be moved?

The tanks on the ship’s hull are moved up and down guided by rails, mounted in the hull of the ship. A gear mechanism drives these guide rails. The gear mechanism is powered by a hydraulic motor which is fully controlled by the ship’s loading computer.

![Diagram of tank system]

**Figure 3.9**

3.5.1 How the computer knows when to move a tank

Figure 3.9 shows an overview of the automation system. The pressure transmitters that are mounted on several places in the hull send their information to the loading computer which will calculate and show the depth of the vessel. Because pressure will increase when at greater depths. This pressure results in an electronic signal which can be read by the loading computer. The height transmitter sends information about the height of the tank to the loading computer. The loading computer will calculate the optimal height of the tanks in which the ship contains a minimum of stress on the vessel. These calculations are bound to manually set parameters which can contain requirements like a maximum depth and stress on the vessel and stability. The computer handles the tanks automatically until the required situation is acquired. The same height transmitters as mentioned above are used to give feedback to the computer to ensure the tanks are at the set height.

3.6 Conclusion

The tanks are connected to its engine and several transmitters. The pressure- and height transmitter send their signal to the loading computer and from there it is possible to send a command to the engine of the tanks to increase or decrease their height. The pressure transmitter makes it possible to measure the draft of the ship on several places (fore-, mid- and aft). To hold the tank in position the holding pin is inserted when given the command. This can only be done on certain points, every 20 cm.
4. Advantages and disadvantages

4.1 Automatic systems
To automate the system, hydraulic systems are being used. Hydraulic pumps, hydraulic cylinders etcetera will be needed, which will take up some space in the ship. The space you need to use for securing the tanks with pins may be larger because this is extra machinery. Another disadvantage of the floatation tank system is that the ship has extra moving parts, causing a bigger risk on system failure. The floatation tanks hydraulic and mechanic system may also need additional maintenance. The ballast water system is probably less complex than the automation system with the floatation tanks, but as it may take a while for ballast tanks to fill completely, the side tanks can be adjusted within a significantly shorter period of time.

4.2 Materials
The good thing about graphene is that it is very strong and lightweight. But you need enormous amounts of graphite ore to produce a small quantity of graphene. The graphene industry is not very developed so, it can be a hard time getting the resources. Polypropylene is a good option because it is cheap and widely used. The downside of it is that it is less sturdy as graphene. For designing a ship with ballast tanks, no special materials are used to produce these tanks, which is a disadvantage for using floatation tanks. Plastics can break whereas steel will bend to a degree, this is a disadvantage. Graphene would not break because it has elastic properties. The reason that is chosen for graphene is that a light weight solution is wanted so it has a minimum effect on the total weight of the vessel and stability when they are inactive.

4.3 Hydrodynamics
The concept of using separate floatation tanks may negatively influence the hydrodynamic of the ship, causing an extra amount of fuel needed. A ship with ballast tanks will not have these problems. Despite the fact that the design with floatation tanks may take up extra fuel consumption, the IMO has made extra rules and regulations for the discharge of ballast water. These ballast water treatment systems will have their own emission and fuel consumption, but will not affect the hydrodynamics of the ship. Hydrodynamic and fuel calculations of both the conventional ship with BWT (ballast water treatment) and the ship designed with floatation tanks were not conducted because this was outside of the project boundaries. Therefore further research needs to be done to determine which system is more environmental friendly, and which one may eventually be the most profitable for ship owners.

4.4 Stability
An application of ballast water on a conventional ship with ballast water tanks is to increase stability. This will cause a ship to increase its draft. In some situations more stability is required, but an increased draft is unwanted. The floatation tanks can be a solution to this problem, because the 5 vertically adjustable tanks can be adjusted to many situations. For example, when the ship is at an appropriate draft but needs extra stability, the floatation tanks can be lowered until the point at which these tanks will touch the water line. This increases the area water line thus the stability, but the ships draft will not be decreased. A disadvantage of this system is that when the floatation tanks are fully submerged the stability decreases rapidly, so when the full the maximum amount of buoyancy is needed it is recommended for safety that the floatation tanks are always a few cm above the water line. A major advantage of these tanks is that they are very fast compared to conventional ballast tanks, the height adjustment can be done instantaneous and can go in a matter of minutes from above water to fully submerged, as where a conventional ballast system will take hours to achieve this.

4.5 Room for cargo / bunkers
An advantage of the floatation tank system is the absence of ballast water tanks (and ballast water treatment system ). This will leave more room for cargo and/or fuel. This is because all space that should be taken by ballast water in conventional ships will disappear because the whole idea of ballast water in the vessel is thrown overboard. The space where nowadays the ballast tanks are placed for example the double bottom could also be used as emergency ballast tanks may the floating tanks malfunction.
4.6 Conclusion

The side tanks will act faster than when one would fill up normal ballast water tanks. But, more systems and moving parts are needed to achieve such a system. The considered materials are stronger and lighter than steel which is a good thing, because when the tanks are lighter more upthrusting force is created compared to heavy steel tanks. When the tanks are heavy, the vessel is heavier and it will go down but it has to go up using more air. The use of separate floatation tanks may be a negative influence on the hydrodynamic of the ship, causing an extra amount of fuel. A disadvantage of this system is that when the floatation tanks are fully submerged the stability decreases rapidly.
5. Final Conclusion

5.1 Design

Normally, a vessel is brought down with ballast water. Instead of bringing her down, the vessel will have an increased depth and the system will bring her up with air when fully loaded with cargo. Using it will eliminate the pollution caused by ballast water. The design of the newly researched system consists of ten floating tanks, five on each side of the ship. Many factors were studied to make one idea the best. Factors like stability, trim, breadth, draft, berthing, the amount of upthrusting force it will deliver and the forces they will bear. After comparing one idea was the best: ten small floatation tanks. This idea is more preferable than using two big tanks and the compression units. Because the large tanks have too much forces gathering in small points. For example, the rotating point of the tanks. This point allows the tanks to rotate to a small degree to change trim. The compression block idea was eliminated because the stability would decrease heavily. Air would be stowed under the vessel. This will give it a balloon-under-water effect resulting in a heavily rolling vessel.

So the concept used is the idea with 10 small floatation tanks, 5 on starboard, and 5 on port side. The shape of these floatation tanks will be hydrodynamic so it will get a small resistance in the water (see figure 5.1). The ship designed in figure 5.2 has 10 floatation tanks that have a length of 20 metres, a height of 7 metres and a width of 2 metres.

5.2 Materials

The materials used for the tanks will be either polypropylene or graphene. Steel has been the reference position of the comparison of the materials. The tank is filled with air which has to be used at its full potential. Steel is too heavy to use as floating tanks. The amount of buoyant force the tanks can theoretically deliver will be decreased because the steel tanks would weigh much more than the lighter materials. Polypropylene is a lightweight plastic, that is ten times stronger than steel. Graphene is an elastic, carbon based material that is very strong and also lightweight. Combining those two materials to an alloy or using either one of them would benefit the system. The weaknesses and strengths of one another would be eliminated. So, the rough design for this idea would be ten small tanks, made from graphene and/or polypropylene.

5.3 Stability

One of the most important factors of safe sailing is stability. A too small stability can lead to capsizing of the ship. The calculated numbers reveal that the buoyant force increases when the tanks are in the water. The AWL will increase the moment the tanks touch the water, therefore the MB increases but will decrease when the tanks are fully submerged. That is why the tanks should not be submerged completely. From the inclining test, the assumption that the stability is at its maximum when the tanks are semi-submerged can be made.
5.4 Automation
To save time and control the system more accurately, the system needs to be automated. A centralized system and controlling system will guide this. Numerous transmitters will compare, measure and send their information about the state of the vessel to the main load master computer. The computer will send a signal to the hydraulic system which will move the tanks. Pins secure the tanks so they will not detach from the vessel.

5.5 Advantages and disadvantages
The biggest advantage the floatation tanks would have is that it is a passive system. Systems nowadays, like Ballast Water Treatment Systems have their own power requirements, fuel consumption and emission in which it is unclear if the environment is impacted positively or negatively. The disadvantages are the operational downsides of moving parts whom need their own maintenance and whom can break. Another disadvantage could be the hydrodynamics of the ship. The floatation tanks could cause more resistance in the water, causing more fuel consumption. The air filled tanks are moving most of the time to balance the ship while sailing, resulting in more maintenance. The ballast water system is mostly used while loading or discharging and requires only a ballast water pump.

5.6 Conclusion
Now to answer to the main question: How can a ship sail efficiently and safely without ballast water using upthrusting air?

The design of the ship makes sure that the resistance of the water on the ship won’t be too high so the fuel consumption won’t rise. Also the material the tank is made off has to be lightweight. Therefore polypropylene or graphene can be used. These materials are not easily damaged. The floatation tanks can be automated by the computer, the input will be in the computer and a small engine for each tank will move the tank up or down. It is an important issue to maintain the safety on the vessel, that’s why the safety pins are secured once the tanks are on their appropriate place, so the tanks can’t move anymore without order from the computer. The floatation tanks also increase the stability of the ship when they are semi-submerged, which also is an extra safety measure. The system is a passive way to eliminate the ballast water problem, because ballast water is no longer needed with this system.

The system used with the floatation tanks is a very good alternative to the conventional ballast water systems. With this system there is no possibility of transporting harmful marine species from one place to another. Although more research needs to be conducted about this system, this research has shown that it is possible for a vessel to sail safely without ballast water using upthrusting air.
6. Recommendations

The tests were done on a block shaped ship, with rectangular shaped floatation, this to simplify the calculations. But it would be a very interesting research to see which shape of the floatation tanks are the most fuel efficient and therefore the most environmental friendly. While conducting our research, the reaction of the ship on heavy weather has not been tested. The safety of the crew is top priority so the logical next step would be to investigate how the vessel will react in very heavy weather and mooring conditions.

During the research, other potential ballast water solutions were found (Stephen, 2008). One interesting solution is the concept of water flowing through the ship from the bow to the stern. On the bow of the ship there are 2 pipe inlets below the waterline that allow water to run to the ballast tanks. Because of the ship speeds and the pressure systems around the ship, the water is able to flow to the outlet, creating a constant water (flushing) flow in the tanks. This ensures that no harmful species can be taken from one part of the world to the other.

It goes without saying that further research need to be conducted about this subject. The commercial part of this needs to be looked at as well. One of the most important things for ship-owners to know is if the costs of the new system is profitable on short or long term, compared to the ballast water treatment systems.
References
Aquariaveldhuis.nl. Krab.

Ballast Water Management. (N.D.). Retrieved December 2013, from International Maritime Organisation:

Ballastwater. (2013, August). Retrieved Januari 2014, from Wikipedia:
   http://nl.wikipedia.org/wiki/Ballastwater


Draught measuring system. (N.D.). Retrieved 2014, from Hoppe Marine:


Polypropylene. (2013). Retrieved 2014, from Vantage Products Corporation:
   http://www.vantageproducts.com/polypropylene.html


PRINCIPLES OF STABILITY. (N.D.). Retrieved 2014, from FAS Military Analysis Network:


Technical Information and Engineering Properties. (N.D.). Retrieved 2014, from Ineos:

Traagheidsmoment. (2013, Maart). Retrieved 2014, from Wikipedia:
http://nl.wikipedia.org/wiki/Traagheidsmoment