HYDROFOILS

Optimisation of cargo ships with the use of hydrofoils

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NT-profile with Physics

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Preface

This school research project (PWS) is made by Peter van Florestein and Claire Seijbel. We are two students studying in 6 VWO at the Koningin Wilhelmina College in Culemborg. When thinking of a subject for the PWS, we immediately knew that we wanted to talk about our shared interest; sailing. Both of us have spent a great portion of our time on the water, mostly in keelboats and sailing dinghies. Claire even competed in a European Championship in the Splash sailing dinghy. One thing that we both noticed in the last few years, was the increasing number of sailing foiling boats. Foiling boats are boats that 'fly' above the water, we wanted to find out why and how the boats could fly and the physics that are behind this phenomenon. This was a perfect topic, because other than our interest in sailing, we also both have the subject of physics. Also, this wasn't a topic on which we could find a lot of information online.

When thinking of a research question, we wanted to find out in what way foiling boats would be useful in our society. The foils under sailboats are mostly for fun, and to make it more spectacular. However, our modern use of transporting over water are containerships. We wanted to find out if the use of foils could be implemented in our modern society to increase the efficiency of transport over water.

We also wanted to thank a few people.

Firstly, our physics teacher, Taco van der Harst who is also our supervisor by keeping us on track and guiding us with regards to thinking of our research question.

Also, Luigi Minerva, a researcher who agreed to do an interview with us and helped us a lot with our research.

Then, Ton Versteegh, who helped and explained the formulas we used during our theoretical experiment.

Finally, Franka Van Geffen, a former technical naval officer, who gave us content-related feedback and helped us with structural changes.

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Introduction

In sailing competitions, there are a lot of sailboats with a hydrofoil. This enhances the performance of the boats. They experience less drag, which makes them go faster. So, less energy is needed to make the boat with a foil go as fast as it would without a hydrofoil. A sailboat gets its energy from the wind. The boats with a hydrofoil also sail more smoothly because they do not sit on the surface of the water, but above it. Because of this, the boats do not need to follow the curvature of the waves. This makes those boats travel smoother. Hydrofoils also are attached to some yachts. Those yachts experience the same advantages, some, however, take shape differently. The yachts still need less energy to go as fast as s fast as they would without a hydrofoil, but they do not take their power from the wind. Yachts are powered by diesel engines, so the boats burn diesel to get energy. Having said that using diesel as an energy source has a few disadvantages: Diesel has become expensive since the war between Russia and Ukraine and burning it is bad for the environment. The use of hydrofoils, however, helps with those disadvantages. Less energy is needed to go fast, and the energy comes from diesel, so less diesel is required. Therefore, some ferries already have hydrofoils: It is cheaper and faster.
Although hydrofoils appear to have a lot of advantages, it is not adapted yet to the oceanic industry. Big containerships do not have any hydrofoils attached to them. This seemed weird to us. It arose us to the question: Could hydrofoils be used to increase the speed and efficiency of cargo ships?
The answer to this question will be found through the following sub-questions:

- What are hydrofoils and how do they work?
- Which forces act upon a normal ship, and what changes with hydrofoils?
- What are the different hydrofoil types, and which one is the best?
- Can we calculate how efficient foils are, in terms of money that is saved with the use of hydrofoils?

Chapter 1 – General introduction to hydrofoils

Hydrofoils might be a new term for most people. However, even if you have not seen hydrofoils, you probably have seen and heard of its much more famous companion, aerofoils, with its best example of wings on an airplane. Where wings on an airplane lift the airplane up into the air, hydrofoils lift the boat above the water.

When looking at the difference between an aerofoil and a hydrofoil, one thing is remarkable, the size of both. While the widest wingspan of a plane is currently 117 meters, most hydrofoils beneath surfboards and dinghies are not larger than 1 meter. This is an advantage that hydrofoils have, they operate in water. Water is around 800 times as dense as air, so you need less wingspan to lift the foil up.

Hydrofoils are used in lots of different areas with different purposes. In sailing and surfing, it is used to increase the speed, and thus make it more spectacular and exiting. In passenger boats, hydrofoils are used to increase the speed and passenger comfort, since the hull is above the water, waves don't affect the boat as much, and the ride is much more comfortable. There is however, one area where hydrofoils are not really used; underneath containerships. It would seem logical to use them, as the way hydrofoils work is by lifting the boat up the water, they decrease the drag of the hull in the water. When the drag is reduced, you can reach speeds that are much higher, with the same amount of energy. This seems advantageous, and further on we will find out if it actually is useful to use hydrofoils underneath containerships and in what way it will be the most effective.

Chapter 2 – Basic principles of a ship

Before it is possible to understand how hydrofoils work and why they are useful in the efficiency of ship propulsion, it is important to understand the basic principles of ships and the forces that acted upon it, without hydrofoils.

In general, the principle of a ship is as shown in Figure 1. Overall concept of energy conversion.

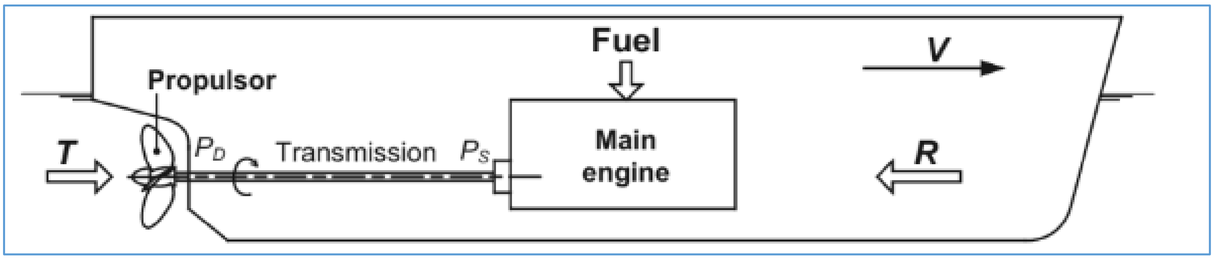


Figure 1. Overall concept of energy conversion (Anthony F. Molland, 2017)

The overall powering system may be seen as converting the energy of the fuel into useful trust (T) to match the ships resistance (R) at het required speed (V). The efficiency of this system will depend on:

- Fuel type, properties and quality
- The efficiency of the engine in converting the fuel energy into useful transmittable power
- The efficiency of the engine in converting the power (usually rotational) into useful thrust (T)

(Anthony F. Molland, 2017)

In foiling, we will focus on the parameters resistance and speed.

2.1 Ship's resistance

The main idea of hydrofoils is to decrease the ship resistance. Ship resistance is the resistance encountered by a ship as soon as it is moving.

There are multiple types of resistance that the ship must overcome, in the table below you can see the types of resistance.

Dry surface	Air Resistance	
Wet surface	Friction resistance	
	Form- or pressure resistance	Rest/Residual Resistance
	Wave resistance	

Looking at the figure below, you can see that most of the resistance is made up of the residual resistance, which is the wave and pressure resistance combined.

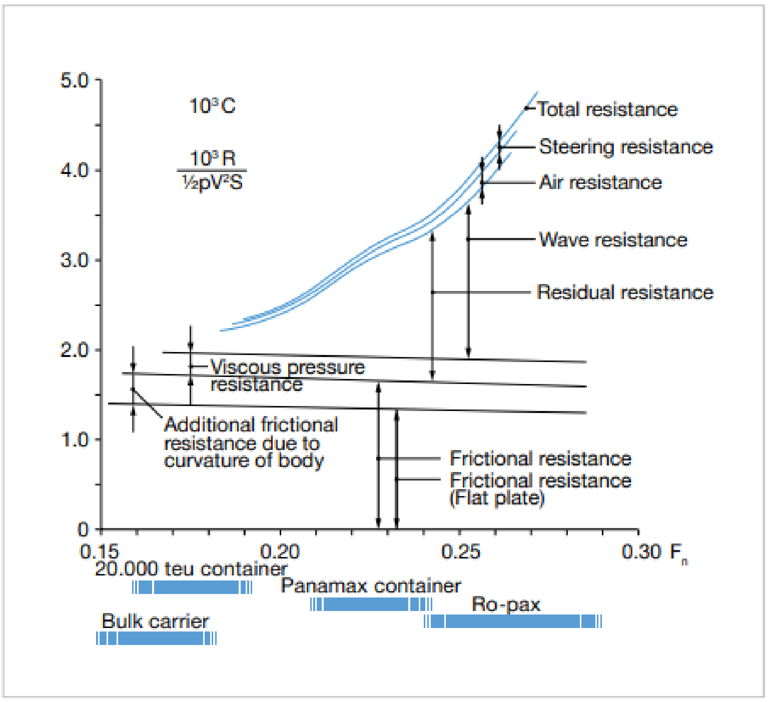
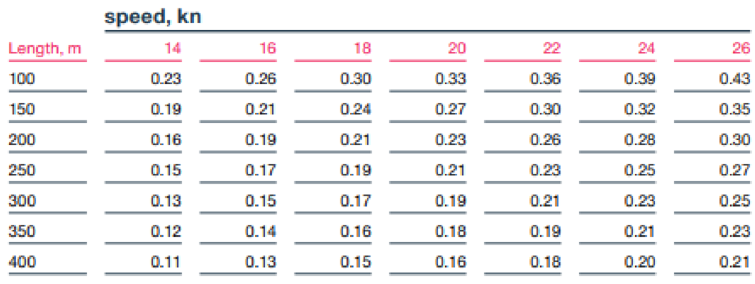


Fig. 1.05: Components of the total resistance as function of the Froude number from Ref. [1.2]



	speed, kn						
Length, m	14	16	18	20	22	24	26
100	0.23	0.26	0.30	0.33	0.36	0.39	0.43
150	0.19	0.21	0.24	0.27	0.30	0.32	0.35
200	0.16	0.19	0.21	0.23	0.26	0.28	0.30
250	0.15	0.17	0.19	0.21	0.23	0.25	0.27
300	0.13	0.15	0.17	0.19	0.21	0.23	0.25
350	0.12	0.14	0.16	0.18	0.19	0.21	0.23
400	0.11	0.13	0.15	0.16	0.18	0.20	0.21

Table 1.02: Froude number as function of the hull length and ship speed

Figure 2 . Resistance as of function of the Froude nr (MAN energy solutions, 2022)

At lower speed, this resistance is mainly caused by the pressure or form resistance and frictional resistance of the wet surface of the ship, which is every part of the hull that touches the water. At higher speed, the wave resistance increases.

The role of the hydrofoil is to create a vertical lift, able to support the weight of a ship in order to lift its hull above the free surface. The goal is to significantly reduce the ship's resistance by:

1. decreasing the wetted area of the ship.
2. decreasing the ship's wave added resistance that is created because of the hydrofoils.

1. Decreasing the wetted area of the ship

If the ship is lifted out of the water, the wet surface reduces resulting in the overall reduction of resistance. (see Figure 2 . Resistance as of function of the Froude nr

The percentage of lift generated by the set of hydrofoils relative to the displacement of the ship is referred as the hydrofoil lift fraction. The lift fraction is equal to 100% in the case of a fully flying ship. A partial lift fraction still allows for reduction of resistance.

2. Waves:

The wake, the waves created by the boat, controls the speed of the ship. A boat creates lateral and transversal waves. The speed of those waves is found by the wave equation:

$$Vp = \left(\frac{g\lambda}{2\pi}\right)^{\frac{1}{2}}$$

V_p	Velocity of the wave (m/s)
g	Gravitational acceleration (9.81 m/s^2)
λ	Wavelength (m)

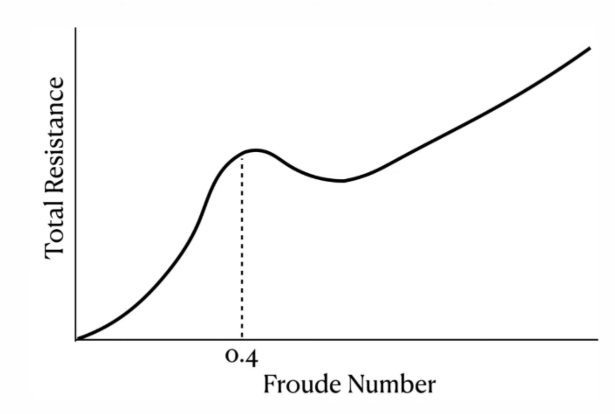
This equation states that the bigger the wave the more speed it has and vice versa. Transverse waves have the most impact on the speed of the boat. If a boat has a slow speed, the waves' speed is also slow, so the wavelength is small. This results in multiple transverse wave peaks along the waterline of the boat. If the boat speeds up, the wavelength increases until the transverse wavelength is the same length of the waterline of the boat. The speed at which the wavelength equal to the length of the boat, is the hull speed. If the boat puts out even more power, to try to go faster, the bow of the boat is pointed upward, and the stern sits in the trough, resulting in the boat getting trapped in the transverse wave. The hull speed can be found using the Froude number:

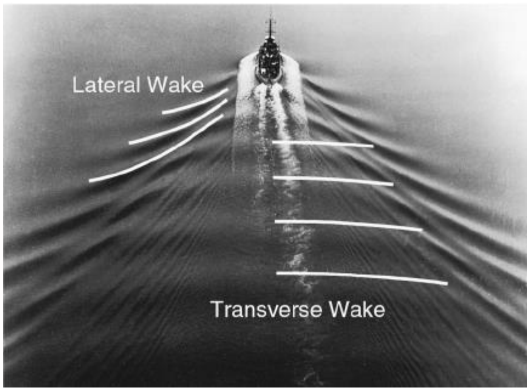
$$Fr = \frac{U}{\sqrt{gL}}$$

Fr	Froude number (non-dimensional)

U	Local flow velocity (m/s)
g	Gravitational acceleration (9.81 m/s^2)
L	Characteristic length (m)

At a Froude number of around 0.4, the boat has reached its hull speed. If a boat tries to increase its speed, the Froude number will increase as well, resulting in more resistance. Thus, it wouldn't be efficient to increase speed, because the drag increases as well. (Rynne, The Physics of Boats, 2022)

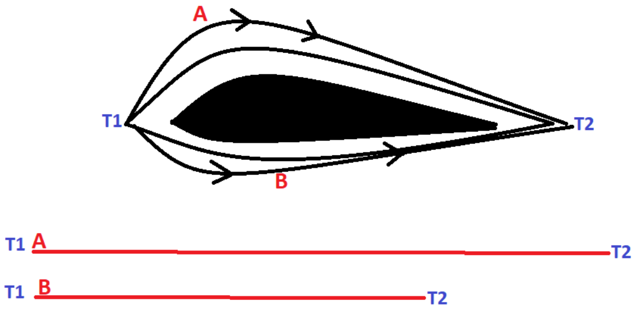




2.2 Basics of a hydrofoil

Then, the hydrofoil itself. A hydrofoil in the basics works like an airplane wing, just with water instead of air. At first, when the boat has no speed, the hydrofoil is submerged under water. When the speed of the boat increases, the foils create lift. When the lift is high enough, the hull of the boat will rise out of the water. Lift is explained by Bernoulli's principle, and it is the basis of how foils can create lift, and thus, fly above the water.

Bernoulli's principle of flight is when water flows around the foil, it takes a greater distance to travel over the top of the foil, than around the bottom. This is because of the shape of the foil. As you can see in figure 2, the water at the top (A), must travel a greater distance, and thus the velocity is increased. Bernoulli's Principle tells us that when the velocity of a fluid increases, its pressure must be reduced, which is a statement of the conservation of energy. This means that the velocity or speed of A is greater than B. It means that the water that goes over the top of the foil, will be ‘stretched out’ and the pressure will decrease. The water is not stretched out at the bottom, so there the pressure will, relative to the top, be greater. Pressure always flows from high to low pressure, and thus, the foil will create lift. (Rynne, How do Hydrofoils work, 2022)



The lift will continue to raise the boat until the downforce of the ship's weight is equal to the lift. At this point, an equilibrium is reached.

Angle of attack

As we explained, the lift is created by the difference in pressure around the wing. This can, however, be optimised. You can do this by changing the angle of attack. This is when the water does not arrive perpendicular to the foil, but at an upward angle. The angle of attack optimises the balance between lift and the drag of the foil, this is dependent on the shape of the foil, and differs with each unique shape of foil.

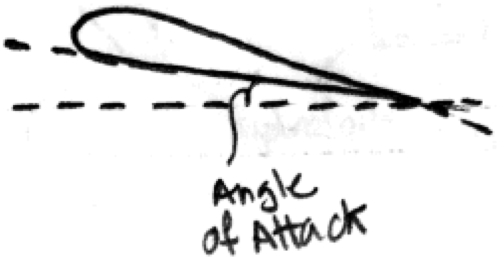
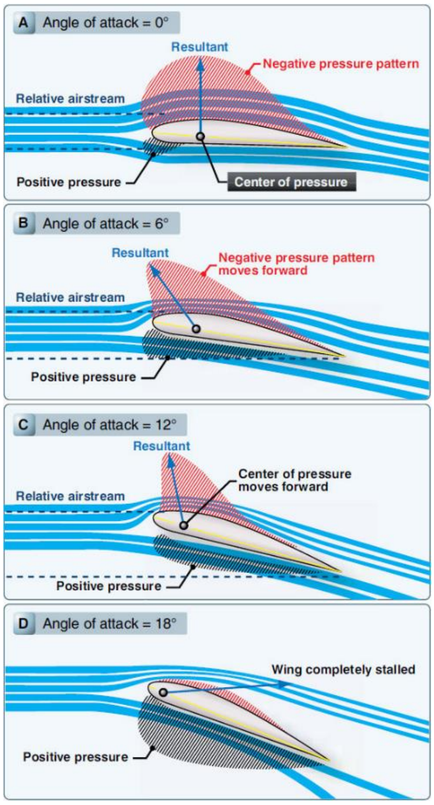


Figure 3. Angle of Attack (Rosado, 2022)

There is a general rule of thumb, at which the theoretical angle of attack is optimal. At around 3 or 4 degrees, the ratio between the lift and the drag is the best, it gives around 20-25 Newtons of Lifting force per every Newton of drag. However, this is an approximation, and the optimal angle of attack is different for every wing profile. (Chapter 6 – Theoretical Experiment)

It is less optimal to increase the angle of attack after that, until around 10 degrees which is a safety limit. The risk of stalling and other environmental factors that make the foils unstable, like waves, wind and current, become too great after those 10 degrees. 15 degrees is the theoretical limit, after that, the foil stalls, which means the drag is greater than the lift. This is dangerous and thus not preferable. (Appendix)

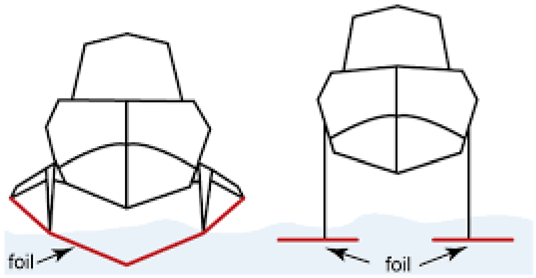


Chapter 3 – Different types of Hydrofoils

3.1 Surface piercing or fully submerged

There are two classes in hydrofoil configurations: Water piercing, often U-shaped, and fully submerged, upside-down T-shaped.

Surface piercing



Surface-piercing foil Fully-submerged foil

Early versions of hydrofoils had a U-shaped configuration because they are self-stabilizing in calm water. However, because of its self-stabilizing nature, it also is very unstable when put in rough water. Waves could create an upwards force on one side of the hydrofoil, while the other side experiences a lack of water, consequently a lack of force. This gives the boat a rolling motion, which could potentially result in the boat capsizing. These hydrofoils would work great in smoother water because there is no need to have a dynamic control programmed into the hydrofoils, as they stabilise themselves, where the fully submerged hydrofoils do not. Also, the water piercing foils are not as efficient as the fully submerged hydrofoils. This is because they will always experience more drag from the water, as the foils have a greater surface area.

Fully submerged

Most hydrofoiling boats nowadays have an upside-down t-shaped configuration. These hydrofoils do not experience effects from waves because they are fully submerged. Hence, they do not create a rolling motion. However, because they are completely submerged, they do not self-stabilize. By changing the hydrofoil's angle of attack the boat can stabilize. Sensors communicate with a computer on board, which determine if and how the angle of attack needs to be changed. But the configuration the sensors and coding of the computer is a time-consuming activity.

3.2 Wing profiles

There are many different types of wing profiles. Wing profiles are the shape of the foil, there are hundreds of different types. Wings profiles for hydrofoils are the same as for aerofoils, as the function of lift is the same, just instead of using air to generate lift, hydrofoils use water to generate lift. Every wing profile has a few parameters to change the shape.

These parameters are:

- The chord length is the distance between the leading and trailing edge. The leading and trailing edge are the first and last part of the foil that touches the water.
- The thickness of the foil is the greatest distance between the highest and lowest part of the foil.
- The chord line is a horizontal line between the leading and trailing edge through the middle of the foil.

- The camber is the upper and lower surface of the foil.
- The camber line is an imaginary line which lies halfway between the upper surface and lower surface, or camber, of the foil and intersects the chord line at the leading and trailing edges. But between the leading and trailing edge the camber line can curve above or below the chord line. (NASA, 2022)

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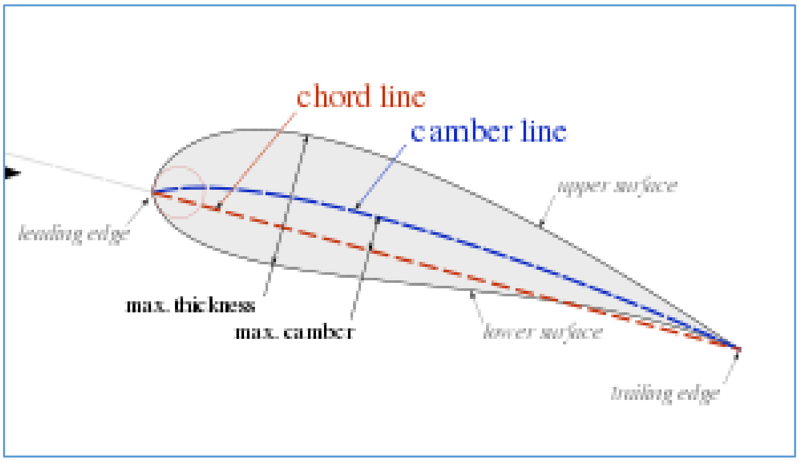


Figure 4. Wing profile (Cleyen, 2011)

The different wing profiles are mostly classified with a NACA (National Advisory Committee for Aeronautics) classification, this was the predecessor of NASA and developed a system to classify every wing foil profile with a system.

This classification system has different series, like the 4-digit, 5-digit or 6-digit series. The more digits, the more complex shapes it classifies. The higher digit series were created when newer shapes were developed, and the lower digit series don't describe enough about the characteristics of the foils. For example, the 7-digit and 8-digit series put emphasis on the maximisation of laminar flow. We will however only explain the 4-digit series, and how its classification system works, because we will use a 4-digit NACA wing profile in our theoretical experiment.

4-digit series:

The four-digit series was one of the first series that were developed. It consists of NACA+4-digits. Each digit indicates a different part of the foil.

- The first digit specifies maximum chamber as a percentage of the chord.
- The second digit specifies the distance of the maximum camber, from the leading edge.
- The third and fourth digit specify the thickness to chord length ratio, in percentages.

When the first two digits are 00, it means that the foil has a symmetrical shape.

For example, when you have the NACA 2415 profile, it has a maximum chamber of 2% located 0.4 chords (or 40%) from the leading edge with a maximum thickness of 15%.

Chapter 4- Other influences

Ship routing determines a route to sail between a starting place and a destination. In theory, the shortest distance would be the shortest voyage if the ocean is calm, and wind and waves would be constant. However, the navigational environment is far more complex, the strong wind, waves and ocean currents may severely affect ships' safety, speed, and fuel consumption in bad conditions.

It is impossible to generalize on these conditions and thus some simplifying assumptions must be made. However, in ships' design, this all needs to be considered. Mentioned below are the factors that influence the forces that act upon the ship and are important when designing a ship with or without hydrofoils but will be neglected in our theoretical experiment. This is because these factors not only influence certain forces on the ship but influence each other as well. In our theoretical experiment, we want to keep these outside factors constant. Therefore, we made a few assumptions, which are further elaborated on in Chapter 6 – Theoretical Experiment.

4.1 General sea and weather conditions

Sea state

Sea state refers to the combination of:

1. **sea waves** are generated by the local prevailing wind. Their height depends on the length of time the wind has been blowing, the fetch (the distance the wind has blown over the water), and the water depth.
2. **swell waves** are the regular, longer period waves generated by distant weather systems. They may travel over thousands of kilometres. There may be several sets of swell waves travelling in different directions, causing crossing swells and a confused sea state. Crossing swells may make boat handling more difficult and pose heightened risk on ocean bars. (Bureau of Meteorology, 2022)

Currents

Currents are driven by wind, water density differences, and tides, which are caused by pressure differences, temperature and salinity variations. Tides create a current in the oceans, which are strongest near the shore, and in bays and estuaries along the coast. These are called "tidal currents." Tidal currents change in a very regular pattern and can be predicted for future dates. In some locations, strong tidal currents can travel at speeds of eight knots or more.

Precipitation

Precipitation in combination with low temperatures might lead to forming of ice or snow and replace and moves the ships' centre of gravity upwards, which induces the risk of capsizing.

Wind does not only influence waves but will also have an effect on the above water hull and bridge of the ship as well. It depends on the size and shape of the bridge and on ship speed.

When sailing in adverse weather conditions, a ship is likely to encounter various kinds of dangerous phenomena, which may lead to capsizing or severe roll motions causing damage to cargo, equipment and persons on board.
It is impossible to generalize on these conditions and thus some simplifying assumptions must be made. However, in ships' design, this all needs to be considered.

4.2 Ships characteristics

Dimensions and tonnage

Types can be distinguished by propulsion, size or cargo type (e.g., bulk carriers, container ships, cruise ships, multi-purpose ships, refrigerated ships, roll-on/roll-off ships, tankers). We focus on the Panamax vessel, a term for the size limits for ships travelling through the Panama Canal. The local Panama Canal Authority prescribe vessel requirements.

The PCA states: “Panamax vessels: Vessels of 30.48 meters (100 feet) in beam or more that comply with the size and draft limitations of the Panamax locks; namely, 294.13 meters (965 feet) in length by 32.31 meters (106 feet) in beam by 12.04 meters (39.50 feet).” (Authority, 2022)

Cargo ships can also be categorized by weight (deadweight tonnage DWT). Cargo capacity of a Panamax cargo ship would typically have a DWT of 65,000–80,000 tonnes, but its maximum cargo would be about 52,500 tonnes during a transit due to draft limitations in the canal. (Lloyds, 2012)

Hull form

Traditionally bulk vessels have been designed to maximize cargo carrying ability at the lowest building cost and not on reducing energy consumption. The outcome has been shoebox shaped vessels with short bow sections. The hull form has a high impact on resistance and therefore the speed of the vessel. Our Panamax vessel should ideally have a more slender design. (Haakon Lindstada, 2014)

Roughness and fouling

Fouling is when organisms attach themselves to the hull of the ship. Fouling can result in a substantial increase in frictional resistance. Extreme cases have been seen where fouling had increased the frictional resistance by as much as 100%, normally the resistance increases up to 20-30%.

Like the fouling, the increased roughness of the hull over time, arising from dents that, for example, developed in the harbour will also increase the frictional resistance of the hull.

Hull appendages

On the hull surface certain add-ons are needed to improve the controllability and manoeuvrability, seakeeping, strength and structural aspects or to fulfil operational requirements. These attachments which alter the flow around the hull are called ship hull appendages. Typical appendages found on ships include rudders, propellers and water inlets and lead to additional resistance. This results generally to a total appendage drag of 2% to 5%. The hydrofoil itself is also a hull appendage. In analyses, the negative effect of the hydrofoil should be considered. However, we do not take this into account in our theoretical experiment (chapter 6).

Chapter 5 –Ideal type of hydrofoils

There isn't one ideal type of hydrofoil, as the ideal type depends on the function of the foils and the function it has in relation to your vessel. It is like with cars. You don't need an expensive race car with a powerful motor if you want to go grocery shopping with your family, but racing in a family car isn't optimal either. There are a few variables that you can adjust and alter to your needs, but which are essential on every hydrofoil.

In this chapter, we will explain the advantages and limitation of choosing a hydrofoil to increase efficiency. Then, we will explain the adjustable parameters of hydrofoils, and which would be our ideal type of foil, which we also use during our theoretical experiment.

5.1 Advantages and limitations to hydrofoil

There are a lot of reasons why using hydrofoils is advantageous, but there are also some downsides. Below are the advantages and limitations of using hydrofoils.

5.1.1 Advantages

A hydrofoil eliminates the negative effects a ship experiences from its wake. As stated in chapter 2, a boat's speed is affected by the waves it creates, mainly the transverse waves. If it reaches its hull speed, it is not beneficial to increase power; the speed will only increase by half of what the power was increased by. If a boat does this, it is planing. However, this is very inefficient. For containership to plane, this would cost a lot of gas, and thus a lot of money. But if a boat has a hydrofoil, as the speed increases, the amount of lift the hydrofoil creates also grows. Eventually, when the boat is foiling and nothing but the hydrofoil touches the water, it creates almost no waves. The hydrofoil has such a small surface area that the waves it creates does not impact the speed of the boat. It can be neglected. So, when a boat starts foiling it does not have the limit of Froude number 0.4, because there is no Froude number. This means that the boat can keep on increase its speed, without eventually having to quadruple the power for only double of the speed. This principle only works when the boat is fully out of the water and only the hydrofoil is submerged.

Another advantage of hydrofoils is that it creates less resistance. A boat without hydrofoils experiences drag from both the water and the air. Water is around 800 times denser than air, so the largest part of the resistance is created by the part of the boat that is in the water. Hydrofoils lift the boat out of the water, so a smaller part of the boat will be in the water. This reduced the submerged: non-submerged ratio of the boat, resulting in less resistance. According to the drag equation, part of the boat which was previously submerged now creates 800 times less resistance. This principle even works when the boat is not yet foiling and is still touching the water.

5.1.2 Limitations

One of the biggest limitations of hydrofoils is the maximum weight of the ship. Hydrofoil ships will only be able to lift a certain amount of weight in the air until the force of gravity is too great. It is now estimated at a weight around 1000 tonnes. In order to increase the maximum weight, you need bigger foils and motors, which in turn make your ship heavier. This then becomes a vicious cycle, in which you need bigger foils to carry the weight, which then, in turn make your ship heavier.

Another limitation of hydrofoils is the sensitivity of the foils. There is a chance that the foils will hit debris in the water which can then break off and cause manoeuvring problems, or even worse, damage the ship itself. Also, the debris can include marine life. When the foils are able to withstand the force of the fish hitting the foils, the fish will most likely not be able to survive.

Another problem that could develop with hydrofoils is the risk of the hydrofoil rising completely out of the water. If a wave is big enough to touch the hull of the ship, the foils will lose its already fragile stability. Since there is a wave, the foil has more room to generate lift, so the ship will rise. After the wave has passed however, the boat will break through the water's surface and will be above the water without touching it. Due to gravity, the ship will fall into the water. The impact this creates could result in breaking the foils, or the ship itself. The ship could also become like a stone skipping over the water. The hydrofoil can bounce on the water if the ship moves fast enough. This bounce could have a negative effect on the cargo and the crew of the ship. In severe cases, the containers or crew can bounce off the ship into the water or break the hull itself. In mild cases, the crew can sustain an injury because of the jerky bounces and the cargo may get damaged. The surface on which the cargo is stored can also get damaged, because of the repeated impact the container will have when they bounce on the ship's floor. This "stone skipping", however, is not likely to occur, since a big cargo ship will not have the power to generate enough speed for this to be a reasonable fear.

Another limitation to foils that is important to keep in mind, is the way of propulsion. When propellers turn, they could create cavitations. Cavitations is when small bubbles of vapor, which create shock waves, this may damage machinery as well as the hydrofoils. Also, it becomes very difficult to control the hydrofoils. It is important to make sure that the hydrofoils are in front of the propeller of the motor to prevent damage. Also, to predict the 'cavitation free range', when it is safe to say that cavitation will not appear, the foils must be subjected to a cavitation study. It is possible to predict cavitation inception by testing scale models using a cavitation tunnel. (Schaub, 2005)

However, through a good engineering design you are able to avoid most these obstacles. You can avoid debris by using a sensitive sensor which will detect small objects in the water. You can avoid the hydrofoils coming out of the water by making sure you can alter the angle of attack in the foils to ensure that in large waves, the ship is stable enough to avoid this. And the placement of the foils is important to avoid cavitations, so a good engineering design will place the foils in front of the propellers instead of behind. The only limitation that is unavoidable, is the maximum weight of the ship, but if you keep the weight of the ship below 1000 tonnes, it isn't a problem at all.

5.2 Adjustable Parameters

Fully submerged versus surface piercing

There are a few different types of hydrofoils, as explained above. But when choosing which of these types is best for your use of hydrofoils, there are a few pros and cons for each type.

When choosing the fully submerged type, the biggest advantage is the amount of lift it produces at a lower speed, compared to the surface piercing type. This is because the vector of the lift force is at a greater angle upwards than the surface piercing foil. Also, fully submerged foils provide a smoother ride, as they have no contact with the waves because the hull of the boat is raised out of the water.

The surface-piercing type of foil has one big advantage, it doesn't need dynamic control. This means that they control the height and stabilise themselves, unlike the fully submerged type. The fully submerged type needs to have a control system to adjust the angle of attack, since it doesn't happen automatically. The downside to this type of foil is that it is less efficient because it experiences more drag than the fully submerged foil. (Globalsecurity.org, 2022)

Below in Table 1 are the biggest (dis)advantages of the fully submerged and surface piercing type of hydrofoil.

	Fully submerged	**Surface piercing**
Advantage	High production of lift Lower Influence of waves, more comfortable	Self-balancing, No dynamic control needed
Disadvantage	Need of dynamic control to stabilise	Lower efficiency

Table 1

Foil and Strut arrangement.

The basic types of placements of the foils are canard, conventional or tandem, see Figure 6. Foil-strut arrangements

A basic rule of thumb, disregarding any other variable, such as how many hydrofoils or which type, is to place the hydrofoils in front of the propeller. This will cancel out the cavitation problem, which is elaborated on in chapter 5.1.2; limitations. Also, the hydrofoils will need to be placed under the centre of gravity of gravity, to be in balance with the weight of the ship. It is important to keep the distribution of the deadweight of the ship in mind. Deadweight is the sum of the weights of cargo, fuel, fresh water, ballast water, provisions, and people. If the deadweight isn't above the hydrofoils, the ship will capsize.

The basic choices in the placement of the foils are canard, conventional or tandem as shown in Figure 6. Foil-strut arrangements.

Ships are considered conventional or canard if 65% or more of the weight is supported on the front or back foil respectively. If the weight were distributed evenly on the fore and aft foils, the configuration would be described as tandem.

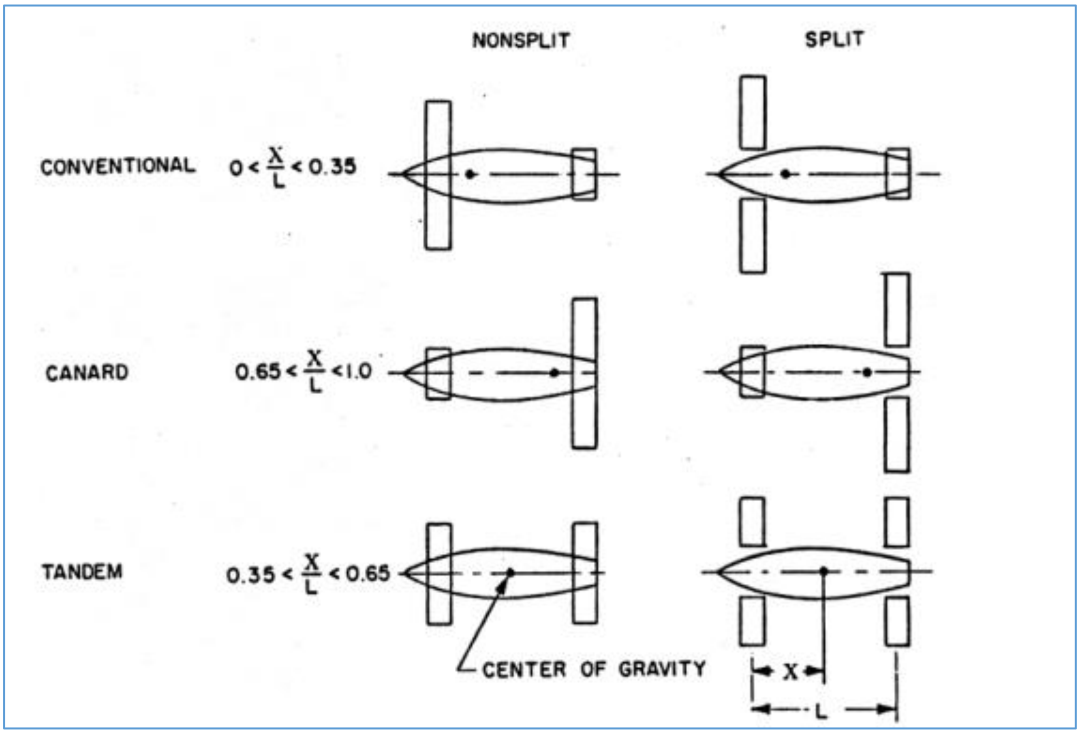


Figure 6. Foil-strut arrangements (Meyer)

5.3 Our ideal type

As we explained earlier in chapter 5, it depends on the objective of the hydrofoil which type, placement and wing profile are most useful for the use. When keeping our goal of making cargo ships more efficient in mind, we have written down our ideal type of foil.

For the type of foil, we have chosen the fully submerged type, because the advantage of the higher production of lift outweighs the need to stabilise the foil. This is because there are dynamic control systems to change the angle of attack automatically through computer systems, which measure the height of the water, and change the angle of attack accordingly.

For the placement of foils, we have chosen to place the foils in the conventional split configuration. This is because these foils follow the same dynamic as a modern airplane and are thus easier to understand how to control. In this configuration the front foils produce the most lift, and the back foil is mostly for stability of the ship. (dmsonline, sd)

The wing profile we think is the most ideal for our objective, is the NACA 0012 wing profile. This is because at a 4-degree angle of attack, when the ratio between the lift and the drag is generally the best, the lift coefficient is 0.5260. When the angle of attack is increased, the lift coefficient changes drastically. From this, you can see that this type of wing profile is very reactive to the change of the angle of attack, which is very useful to create lift efficiently. (Colley, 2011)

Chapter 6 – Theoretical Experiment

To find out if hydrofoils really make a cargo ship more efficient using them, we did a theoretical experiment. During the experiment, we calculated how much money you save using them, and if it is enough to weigh up to the costs of producing and maintaining them.

6.1 Assumptions

While doing the theoretical experiment, we had to make a few assumptions. Below are all the assumptions we made during the experiment:

- No fouling, roughness and/or hull appendages were taken into account.
- No wind, currents, waves or other weather conditions were considered.
- No fouling, roughness and/or hull appendages were considered.
- The boat's hull is shaped as a rectangular block, with its smallest face forward.
- Only residual resistance was calculated with, the resistance created because of air and friction was neglected. (See chapter 2.1 Ship resistance)
- The hydrofoil will always produce its maximum lift.
- The hydrofoil will always be at a 4-degree angle of attack.
- The lift and drag coefficient are based on a 2d model, not a 3d model.
- When the height is adjusted because of the hydrofoils, the width of the ship does not change.
- The diesel engine has a 50% efficiency; this is always constant.
- Heating value is $4.4 * 10^{17}$ Joules/kg.
- There is no other energy loss than the engines efficiency, so 100% of the force generated by the diesel engine turns into forward motion.
- The diesel prices are Rotterdam ports' diesel prices (at the time of writing, December 2022).
- Our cargo ship travels $5.766*10^{8}$ m per year. This is the average distance travelled by containerships. (Akkayaoglu, 2015)
- Our cargo ship always travels at cruising speed, which is 24 kts.

6.2 The equations

The drag that a boat experiences can be calculated using the drag equation.

$$F_{d,b} = \frac{1}{2}\rho c_d A_b v^2$$

$F_{d,b}$	Drag force of a **b**oat in N
ρ	Density of the water in kg/m^3
$C_{d,b}$	The **b**oat's drag coefficient (dimensionless)

A_b	Area of the **b**oat perpendicular to the flow; frontal area in m^2
v	Speed in m/s

The frontal area of the boat can be calculated using the following formula, because the hull of the ship is a rectangular block:

$$A_b = w \cdot h$$

w_b	Width of the boat in m
h_b	Draught of the boat in m

This formula needs to be rewritten to take the area of the foil into account.

$$F_{d,b+f} = \frac{1}{2}\rho c_{d,b}\left(A_{d,b} + A_{d,fc}\right)v^2$$

$F_{d,b+f}$	Drag force of a **b**oat and hydro**f**oil in N
$A_{d,fc}$	**C**ompensate frontal area of the hydro**f**oil in m^2.

The area of the hydrofoil needs to be compensated, because calculating the drag force created by the hydrofoil requires a different drag coefficient than the boat's drag coefficient. This compensation can be done using the following formula:

$$A_{d,fc} = A_{d,f} \cdot \frac{c_{d,f}}{c_{d,b}}$$

$A_{d,f}$	Actual frontal area of the hydro**f**oil in m^2
$c_{d,f}$	Drag coefficient of the hydro**f**oil (dimensionless)

$$A_{d,f} = w_f \cdot h_f$$

w_f	Width of the hydrofoil m
h_f	Height of the hydrofoil in m

The hydrofoil also generates lift, reducing the frontal area of the boat, because part of the boat, which was previously submerged, now is above the waterline. When taking this into account in the drag equation, the following happens:

$$F_{d,b+f} = \frac{1}{2}\rho c_{d,b}\left(A_{d,b} + A_{d,fc} - \Delta A\right)v^2$$

ΔA	Difference in surface area created by the hydrofoil in m^2

To find ΔA, we have done the following:

$$\frac{F_l}{g} = m = \rho V = \rho lwh$$

F_l	Lift force created by the hydrofoil in N
g	Gravitational acceleration 9.81m/s^2
m	Mass in kg
ρ	Density in kg/m^3
V	Volume in m^3
l	Length of the ship in m
w	Width of the ship in m
h	Draught of the ship in m

In the calculations, we want to know the difference in height between a ship with a hydrofoil and one without, so the height will be noted as Δh. The width of the ship does not change. From this can be concluded that ΔA = Δh·w

$$\frac{F_l}{g} = \rho l \Delta A$$

By rewriting the formula, ΔA can be found.

$$\Delta A = \frac{F_l}{g\rho l}$$

By substituting ΔA for $\frac{F_l}{g\rho l}$ in the drag equation, the drag a ship with hydrofoil experiences can be calculated.

$$F_{d,b+f} = \frac{1}{2}\rho c_{d,b}\left(A_{d,b} + A_{d,fc} - \frac{F_l}{g\rho l}\right)v^2$$

The equation to find Fl is $F_l = \frac{1}{2}\rho c_l A_l v^2$

ρ	Density in kg/m^3
c_l	Lift coefficient (dimensionless)
A_l	Total surface area of the hydrofoil in m^2

v	Speed in m/s

By filling this into the equation the formula changes to

$$F_{d,b+f} = \frac{1}{2}\rho c_{d,b}\left(A_{d,b} + A_{d,fc} - \frac{\frac{1}{2}c_l A_l v^2}{gl}\right)v^2$$

ρ is crossed out in the fraction, because both densities are the density of seawater, so it is the same value. Hence the simplification of crossing them out.

By calculating the difference between the drag of a boat with a hydrofoil and without, you can calculate the drag force saved by the hydrofoil.

$$\Delta F_d = F_{d,b} - F_{d,b+f}$$

ΔF_d	The difference of drag created by the hydrofoil

With this value, using the work law, you can calculate the energy saved.

$$W = F \cdot s = \Delta F_d \cdot s$$

W	Energy saved due to the lift created by the hydrofoil
s	Distance travelled in meters

Using the heating value and efficiency, you can calculate the amount of fuel saved ergo how much money is saved.

$$m = \frac{W}{r_v \eta}$$

m	Mass of the fuel in kg
r_v	The heating value in J/kg
η	Efficiency of the engine

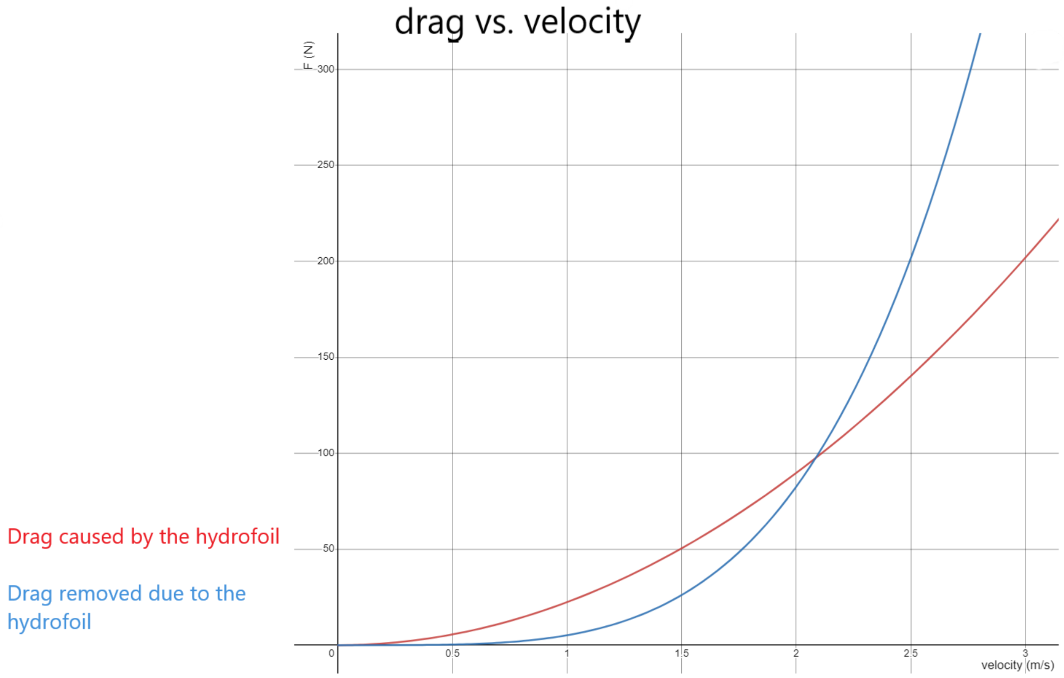
6.3 Values used for theoretical experiment

Physical quantities	**Value**	**Source**
ρ	1025 kg/m^3	(Density of Seawater, sd)
$C_{d,b}$	0.85	(welcome, 2014)
v	24 kts = 12.3 m/s	(The Geography of Transport Systems, sd)
w_b	32.31 m	(Jassal, sd)
h_b	12.04 m	(Jassal, sd)
w_f	$3 \cdot 7.905\,m = 23.715\,m$	(NavSource Online, 2022)
h_f	The NACA 0012 has thickness of 12% compared to its chord, which is 0.32 m.	(NavSource Online, 2022)
$c_{d,f}$	Taking the values of X-foil, the drag coefficient is 0.0057 at an angle of attack of 4°.	(Colley, 2011)
g	9.81 m/s^2	(Bouwens, 2013)
l	289.56 m	(Jassal, sd)
c_l	Taking the values of X-foil, the lift coefficient is 0.5260 at an angle of attack of 4°.	(Colley, 2011)
A_l	3 times a hydrofoil, NACA profile 0012, the measurements: l = 2.699 m, w = 7.905 m, h = 0.32 m. (biggest hydrofoil to ever exist) By filling this in, the calculator gives a value of 64,065 m^2.	(NavSource Online, 2022)
s	$5.766 \cdot 10^8$m	(Akkayaoglu, 2015)
r_v	$4.4000 \cdot 10^7$ J/kg	(Fuel Oils – General Aspects, sd)
η	50% = 0.50	(Information, 2018)

6.4 Results of theoretical experiments

Filling these values into the equation results in the following answer: the total mass of the full saved by the hydrofoils is $3.0 \cdot 10^3$ metric tons. In Rotterdam the fuel price is $520.00 per ton. You can calculate the total amount of dollars saved by multiplying the fuel price by the mass of the fuel. This results in a gross amount of 1.56 million dollars a year. This is around 1.5 million euros a year.

By rewriting the formula $F_{d,b+f} = \frac{1}{2}\rho c_{d,b}\left(A_{d,b} + A_{d,fc} - \frac{\frac{1}{2}c_l A_l v^2}{gl}\right)v^2$, you can plot a graph at which speed the hydrofoil starts producing more lift than drag. The red line is the drag created by the frontal area of the hydrofoil: $F_{d,f} = \frac{1}{2}\rho c_{d,b} A_{d,fc} v^2$. The blue line is the amount of drag force removed by the hydrofoil: $F_{d,\,removed} = \frac{\frac{1}{2}c_{d,b}\rho c_l A_l v^4}{gl}$. At the intersect point, the hydrofoil starts removing more drag than it is producing. From this point onward, the hydrofoil will be beneficial, without looking at the cost to produce one. This point is around 2.1 m/s.



Discussion

We had to make a lot of assumptions, because otherwise the calculations within the theoretical experiment would become too complex. The assumptions that simplified the calculations were:

- The lift and drag coefficient are based on a 2d model, not a 3d model
- No wind, currents and waves are considered
- Perfect weather conditions were used, so no precipitation or extreme temperatures
- No fouling, roughness and/or hull appendages were considered
- The hull is shaped as a rectangular block
- When the height is adjusted because of the hydrofoils, the width and length of the ship do not change
- Only residual resistance was calculated with, the resistance created because of air and friction was neglected

We also made a few assumptions where we took an average. This average does not change in the calculations. In real life, however, its values change from moment to moment or from ship to ship. These assumptions are:

- The hydrofoil will always produce its maximum lift
- The hydrofoil will always be at a 4-degree angle of attack
- When the height is adjusted because of the hydrofoils, the width of the ship does not change
- The Diesel engine has 50% efficiency, and this is always constant
- Our cargo ship always travels at cruising speed, which is 24 kts
- The distance travelled by a cargo ship in a year is $5.766 \cdot 10^8$m

Furthermore, we used a lot of 2d models to gather information instead of 3d models. This use of 2d models might have given us an inaccurate image of the situation. For example, the lift coefficient is calculated in a 2d model. The world we live in, however, is a 3 dimensional one. Because of this, the lift coefficient is likely to be a different number than the one calculated in the model. Having said that, the lift coefficient calculated in the 2d model will be a close proximity to what it is in the physical world (Appendix). By virtue of the number being a close proximity, we still think it is an accurate representation of the lift coefficient for the theoretical experiment. The same rules for the hydrofoil's drag coefficient.

Another example is the efficiency of the diesel engine. Every type of diesel engine has a different efficiency. Even within a single type of diesel engine there will be a different type of efficiency at a certain timestamp. If you line the same type of diesel engine up in a line, some engines might work at peak efficiency while others will work at the average or maybe even at bottom efficiency. (E.Nam) For the calculations to be the most reliable it can be, we chose to use the average.

However, not all of the assumptions that we did, resulted in a negative way for the conclusion. There are a few assumptions that might impact our result in a positive way. These assumptions are:

- The ships’ hull is shaped as a rectangular block, with its smallest face forward.

Of course, a ships’ hull isn't normally shaped like a rectangular block, but it made our calculations easier. In reality is the hull of a ship more streamlined, especially the bow. This means that frontal area of the ship experiences more resistance than in reality. When it hits the bow seen from front, the sides of the ships are rounded. This means that the frontal area is smaller. Also, because the ship shape is streamlined, the water is 'guided' down. In the assumption that we made, the frontal area was a vertical plane, which means that the resistance of the frontal area was a lot higher as well.

Another assumption that positively impacts our theoretical experiment is:

- When the height is adjusted because of the hydrofoils, the width of the ship does not change.

In reality, a ships' hull is rounded down to, as mentioned before, make the hull more streamlined. This means that when the foils lift the ship upwards, the frontal area doesn't only decrease in the vertical dimension, but in the horizontal dimension as well. This impacts our experiment in a positive way, as the frontal resistance is in reality less than what we calculated with.

The third assumption we made is:

- The hydrofoils attached to the USS Plainview are the biggest hydrofoils physically possible.

To calculate the lift creating area of the hydrofoil, we took the sizes of the hydrofoils of the USS Plainview. This was, and to date still is, the fastest and biggest hydrofoiling ship to have ever existed. The ship also contained the biggest hydrofoils ever built. Because of this, we concluded that the weight of the hydrofoil was closest to the maximum weight a hydrofoil could be; at a certain point as the hydrofoil’s weight increases, the hydrofoil starts creating more drag and gravitational forces than it creates lift. Since we estimated that these hydrofoils would be close to that maximum, we used the dimensions of these hydrofoils in the calculations. However, this might not be true anymore, because new materials have been discovered since the creation of the USS Plainview, which might have a smaller density than the materials used for the USS Plainview’s hydrofoils. Also, the hydrofoils attached to the USS Plainview might not be the biggest that was feasible at the time of creation. It is possible that the designers of the ship calculated the area of the foil after the first designed the ship. Because they knew how much the ship would weigh, they could calculate the amount of force needed for the ship to fly on its hydrofoils. Since they might have known how much lift force was needed, they could calculate the surface area needed. Due to these factors the area of the hydrofoils could possibly be bigger than the values we used in our theoretical experiment. If this is the case, more lift will be produced, so the hydrofoils will be even more effective than it already is.

We think that the assumptions we made, both impacted our theoretical experiment in positive and negative ways. However, we hope that because of this, the assumptions compensated each other. We conclude that further research must be done to find the limits of the use of hydrofoils and if these results are also applicable to other types of vessels or cargo ships.

Summarising Conclusion

When reflecting on our PWS, we answered all of our sub-questions. The question: "What are hydrofoils and how do they work?", we answered in Chapter 1 – General introduction to hydrofoils and 2.2 Basics of a hydrofoil. In these chapters, we explained that hydrofoils are the same to a ship, as wings to an airplane. The biggest principle behind the question of how hydrofoils create lift, is explained by Bernoulli's principle. The principle explains that the pressure at the bottom of the foils is higher than, at the top. Pressure will always go from high to low, and thus lift is created.

The question: "Which forces act upon a normal ship, and what changes with hydrofoils?", is answered in Chapter 2 – Basic principles of a ship. In this chapter we explained the basic principles of a ship, with the concept of energy conversion within a ship. Then, we focused specifically which different types of resistance act on a ship (without hydrofoils). Then, in 2.2 Basics of a hydrofoil, we explained what happens when a hydrofoil is added.

To the question: "What are different hydrofoil types, and which one is the best?", we answered in Chapter 3 – Different types of Hydrofoils, and 5.3 Our ideal type. In Chapter 3 – Different types of Hydrofoils, we described that there are fully submerged and surface piercing hydrofoils, and the different types of wing profiles where every profile has its own distinct characteristics. In 5.3 Our ideal type, we explained which of the choices we made in relation to the type, placement and wing profile, for our goal of making a cargo ship more efficient.

Then, "To calculate how efficient the foils are in terms of money that is saved with the use of hydrofoils", we did a theoretical experiment in Chapter 6 – Theoretical Experiment. During this chapter we found that the money that is saved with the use of hydrofoils, calculated with our values, is around 1,5 million euros.

To answer our main question: "Could hydrofoils be used to increase the speed and efficiency of cargo ships?" We conclude that hydrofoils are an effective way to increase the speed and efficiency of cargo ships. However, as stated in the discussion, further research must be done to find the limits of the use of hydrofoils and if these results are also applicable to other types of vessels or cargo ships.

Appendix

Interview with Luigi Minerva:

https://youtu.be/6WCj8vnjKA8

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