Hydrofoil fixture load analysis

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Abstract:

The purpose of this thesis is to quantify the fixture loads of a hydrofoil structure. A fixture is a device that transfers a load between a mast and a hull of a hydrofoil. These loads are dependent on the vessels operational modes, (i) accelerating, (ii) foiling, (iii) deceleration. The loads are in all cases combinations of compressive and bending loads.

The thesis demonstrates the largest loads exist during acceleration, before the vessel reached the foiling mode. The bending fixture loads are biggest before the vessel is completely lifted out the water. Compressive stress in the fixture however increases the more the vessel is lifted from the water due to fact that buoyant force gradually stops to affect on a hull, and its' mass shifts on a cross section of a mast. As soon as the craft's hull leaves the water, and whole hull's mast renders compressive load on a fixture and mast.

A detailed FEA analysis with COMSOL is performed in 2 steps, in the first step a pressure field on the hydrofoil is calculated at a given flow speed. The FEA solver uses turbulent model. In second step the pressure field is used as input to calculate the static stresses on the hydrofoil. The hydrofoil fixture must transfer these loads. The first step of the fluid dynamic FEA analysis is computationally more demanding than the second step. Calculation time per velocity was approximately 20 minutes per iteration. The solutions are found using fluid mechanics simulation of a given foil shape while demonstrating the lift off or onset of foiling at the speed 5.42 meters per second. The vessel's hull had a mass of 1500 kilograms, the wingspan of a hydrofoil was 2 meters, the height of a mast was 1 metre.

Maximum combined (compressive and bending) load observed to be 0.86 MPa and occurs at liftoff speed in corners of a leading and a trailing edge of a mast. The model included a compression stress from the hull's mast. Hull's technical data is included in appendix. Maximum bending stress observed to be 0.12 MPa. The speed was limited to 20 meters per second since latter speed is an optimal and is rarely exceeded in real life operation.

The sudden crash mode was not studied in current thesis due to abundance of factors that the software must consider in order to achieve proper results.

Keywords:	Finite Element analysis, FEA, Shear stress, Hydrofoil, Hydrofoiling, Fixture
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Contents

LIST OF SYMBOLS

m – mass [kg]

$\vec{v}$ – velocity [m/s]

$\overrightarrow{F_n}$ – Normal force [N]

$\overrightarrow{F_{lift}}$ – Lifting force [N]

P_x – pressure [Pa]

h - height [m]

$\sigma -$ stress [Pa]

$F -$ Load [N]

$l -$ Length [m]

$Z -$ section modulus of the cross $-$ section $[\mathrm{m}^3]$

M_x – bending moment [N·m]

I- moment of inertia $[\mathrm{kg{\cdot}m}^2]$

$c -$ distance from neutral axis to the edge [m]

$\Delta x -$ change in length, x $-$ directioal [m]

$\rho -$ density $[\mathrm{kg{\cdot}m}^3]$

$u -$ flow speed [m/s]

L $-$ characteristic linear dimension [m]

$\mu -$ dynamic viscosity $[\frac{\mathrm{N{\cdot}s}}{\mathrm{m}^2}]$

$L =$ Lift force [N]

$C_l =$ lift coefficient [Unitless]

$\rho =$ fluid density $[\mathrm{kg{\cdot}m}^3]$

$A =$ surface area $[\mathrm{m}^2]$

E - Modulus of elasticity [Pa]

FIGURES AND TABLES

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1. INTRODUCTION

An idea for this thesis was born in 2020, when the author, who had previously made a working prototype of a hydrofoil encountered with an issue of an insufficient stiffness of an element that connects the mast of a hydrofoil to a craft body. At that time the whole construction broke at extremely low speeds, which did not even exceed 5 kilometres per hour. Figure 1 shows a prototype.

Figure 1. Hydrofoil prototype (Pozhidaev,2021)

The aim of this thesis is to investigate what peak loads occur in fixture during operation modes. In our work we will specifically focus on maximum loads the fixture is expected to transfer. The study is performed completely digitally, with the help of COMSOL engineering software, that allows us to run a simulation of a real-life events with precision.

1.1 Objectives

The aim of this thesis is to study what loads a fixture of a hydrofoil experience during various operational regimes. A fixture is a crucial element that connects the mast of a hydrofoil to a hull, therefore helps to transfer loads from mast to a hull. The study will be conducted with the help of a computational software, which allows us to simulate a physical events – COMSOL. The following thesis' framework is going to be fully theoretical. We will investigate following issues:

1. The maximum stress that a hydrofoil's components can handle
2. Maximum stress magnitude occurring in the system during an operation
3. Stress magnitudes occurring in the a «wing-strut-hull» system at different speeds, or in other words, what stresses does a fixture experience during different modes. These modes are:

    3.1 Acceleration – fixture experiences bending load from oncoming water masses.

    3.2 Lift-off – a compressive load is added to an existing bending load. Compressive load caused by a hull's mass.

    3.3 Deceleration. The craft is slowing down transfers from hydrofoiling mode to water displacement mode.

2.LITERATURE REVIEW

2.1 Purpose

This foremost reason for this thesis is to theoretically identify and pinpoint a fundamental peak stress that emerge on such complex craft as a hydrofoil vessel. Doing latter, in perspective would allow for further studies on the topic of hydrofoil safety measures, better material selection for elements and most efficient operational speeds.

We will be using a term called «Von Mises stress» in our study. Von Mises stress is a stress criteria that allows us to identify if a material would yield at a given point. [1]

2.2 Hydrofoiling

A hydrofoil is a vessel that is sustained above the water surface during normal operation mode due to the hydrodynamic forces that occur on the submerged airfoil.

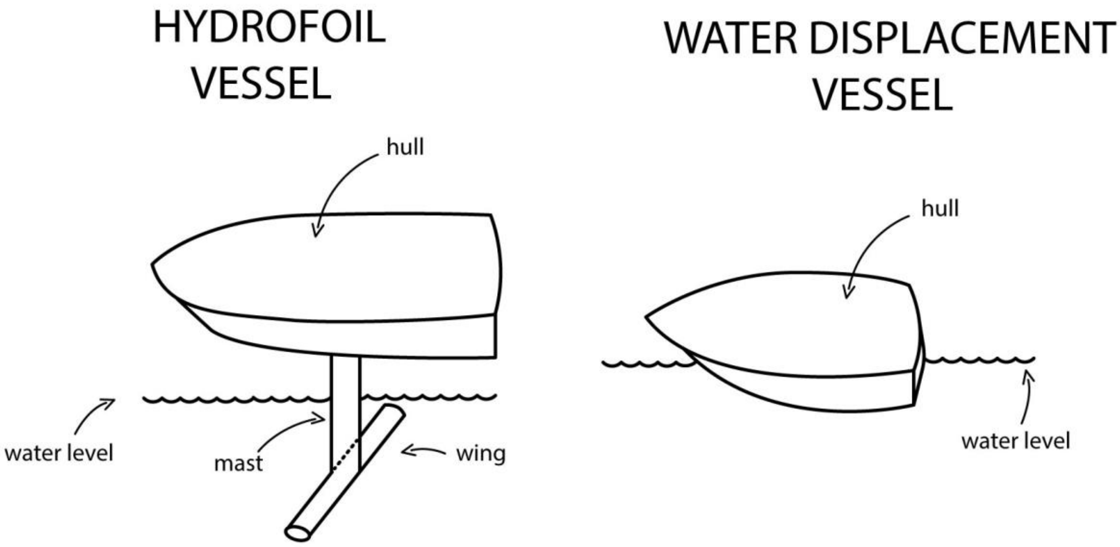


Figure 2: Difference between hydrofoil and water displacing vessel (Pozhidaev 2021)

A fundamental difference between the working principles of a regular water displacing vessel and hydrofoil is shown on a Figure 2.

The drag on the conventional water displacing vessel is due to amount of wetted surface and is the cause of speed limitation. As such it is presenting the loss of efficiency for the conversion of engine power to forward speed. A hydrofoil vessel has as compared to a displacement vessel a significantly smaller wetted surface and can therefore move much faster and with a higher efficiency.

Considering efforts toward sustainable transport solutions, hydrofoiling is environmentally friendlier than displacement shipping as seen for the fuel per mile ratio for comparable vessels displacements.

2.4 Background and History

A marine industry has always been one of a crucial way of transporting objects, whether it's a group of people wishing to travel, goods to be delivered, or anything else. When it comes to a travelling or transporting goods on a distance, an operator inevitably faces the question of effectiveness and performance. In other words, we want a vessel to travel as far as possible, consume small amount of fuel, and travel at high speed.

Hydrofoil vessels are a fascinating alternative to a conventional vessel since they combine speed and relatively low fuel consumption in comparison to water displacing vessels.

Hydrofoils operate using an underwater wing that is connected to a single, or in case of a heavy vessels, to a series of struts, which in term, carry a load of a hull of a vessel.

There first successful hydrofoil construction belongs to Alexander Bell, also famous for telephone invention. He began the development in 1908 and named his invention “HD-1”. The finished craft was launched in 1911 and achieved speed of 72 km/h. In 1919 the fourth model, “HD-4” achieved unbelievable, for that time, speed of 114 km/h [2].

Figure 3. HD-4 Hyrdofoil (Government of Canada, 1909) [27]

First passenger vessel was created in 1952 by German engineer Hans von Schertel. His craft had a displacement of 60 tons and was able to carry up to 32 passengers at the speed up to 65 km/h. At the same time hydrofoil vessel development was also conducted in Soviet Union. From the 1950s to 1980s the country developed several vessel types for civil applications. Some of them are used even today, for instance “Meteor” [3].

Not only hydrofoils were developed for civil use, but they also had a decent military potential. Several countries such as Russia, United States, Germany and Italy have developed their own hydrofoils for military uses. The main advantage of hydrofoils over conventional vessels is an ability to travel over minefields, increased speeds and payload capacity. Several vessels made by USSR are worth of mention. Those are:

A Project 206M ”Shtorm” – a torpedo boat built in 1971 (figure 4). Could reach the speeds up to 80 km/h. Had a range of 2300 kilometers (Taras. A. 2008) [20]

A MRK-5 “Sarancha” (figure 5) – hydrofoil missile boat. Built in 1973, could reach speeds as high as 107 km/h, had a range of 1300 kilometers (Encyclopaedia of Ships)[21].

Figure 4. Project 206M (US Navy, 1984) [23]

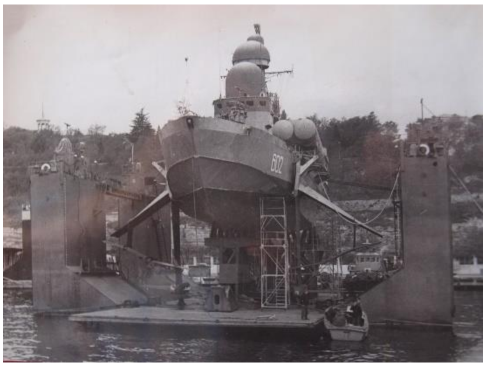


Figure 5. MRK-5 (Babkin M. 1988) [24]

The United States started to work on military hydrofoils in 1950s, which lead to the creation of “XCH-4” hydrofoil, however, it was not yet a combat capable weapon, but rather an experiment (C. Lester, 1961)[22].

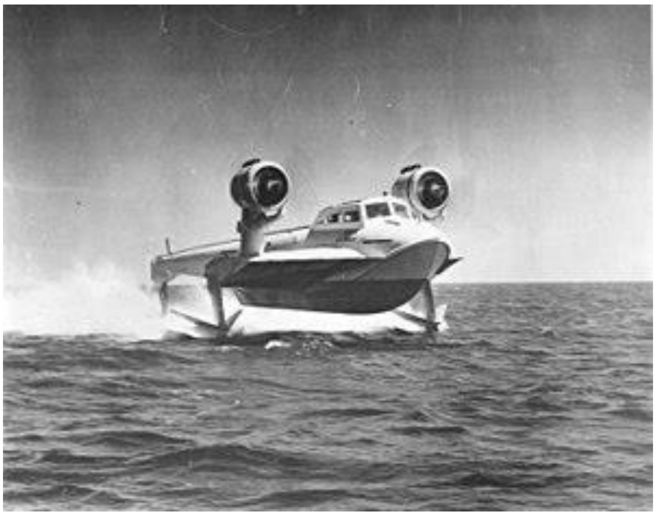


Figure 6. XCH-4 experimental hydrofoil (Unknown author, US Navy, 1950s)

Figure 7. USS "Aquila" (D. Taylor, March 1st, 1986) [25]

Years after, the US finally built several types of military hydrofoils. One of them is USS "Aquila". It had a displacement of 259 tons and could reach the speed of 89 km/h.
Although military are doesn't endeavour to implement more hydrofoils into their troops, nevertheless, several countries have hydrofoils in their military service.

Civil hydrofoils and leisure boats with foil surfaces are also developing in fast tempo.
Yachtsmen are prone to switch to hydrofoils due to higher speeds, and maneuvreability, that gives people more of a pleasure.

Windsurfing and conventional surfing users are now more often looking for modifications of their boards via addition of a foiling surface underneath the boards that gives them higher speeds and paves the way to manoeuvres that were previously unimaginable (figure 8).
Recently several trends on the electric vessels with foil surfaces can also be observed. Manufactures are now increasing the number of crafts for private use equipped with foil surfaces that are fuel efficient, sleek and fast (figure 9).
The foils designs are also changing and shift towards the "V" shaped, surface-piercing foils on a full-scale crafts (not considering small crafts as a surfboards). In the past manufactures were likely to equip their products or vessels with fully submerged foils.

Figure 8. Hydrofoil surfboard (Naish, 2019) [28]

Figure 9. Private leisure hydrofoil (Quadrofoil , 2021) [29]

2.5 Performance

The main idea of the hydrofoil is drag reduction by lifting the vessel's hull out of the water. However, the foil requires certain speed to generate enough lift to be capable of supporting the vessel´s body. Before "take-off" speed is achieved, vessel displaces the water to move forward, therefore the fuel consumption is similar to the conventional marine craft. The situation changes once the boat achieves the speed required for the foil to lift the hull. The upper part of the vessel does not anymore create drastic amount of drag, therefore less power is needed to maintain the set speed (Besana, Gilberto. 2015) [4].

The speed to drag graph is presented on figure 10.

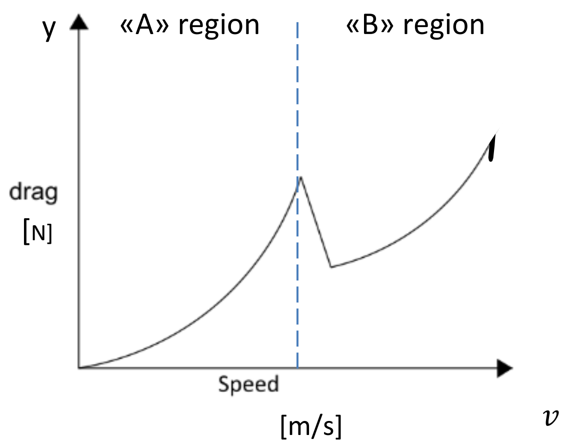


Figure 10: Speed to drag diagram

The «A» region represents water displacement mode, before the foil starts to lift the craft out of the water. The dashed line represents the moment when the speed is enough for the foil to generate enough lift to start lifting the hull out. At that moment the drag significantly reduces, however the speed increases further. Decrease in drag is manifested to a fact that with the speed growth, the lift increases, consequently the hull, that was previously creating a major part of a drag, rises, thus the only part that keeps creating drag is a mast and an airfoil. «B» region represents the hydrofoiling mode. We observe that after rapid hydrodynamical resistance drop, the vessel gradually starts to experience an increase in drag. This is explained by a simple fact - there must be a lifting surface under the water, otherwise the lift could not be generated. However, the foil itself is a rigid body, and obviously generates drag as the body moves forward. The more speed the vessel gains, the more drag an underwater body creates. The stress in «B» however, might exceed peak stress value in «A» region, but only in one case – if we would continue to accelerate in hydrofoiling mode. In our research we limited the speed to 20 meters per second.

2.6 Purpose of Hydrofoiling.

In past two decades hydrofoils, especially in civil sector, have gained significant popularity. Today, hydrofoil technology is not limited only on civil and military vessels, but is used also in entertainment and sports sector. Hydrofoils became so versatile and prevailing to conventional yacht design, that oftentimes sea sailing championships are organized exceptionally for sail vessels with foils. The purpose of hydrofoil, therefore are:

1) Significant drag reduction
2) Reduced fuel consumption
3) Increased speeds

3. METHOD

3.1 Hydrofoil operational loads

A hydrofoil, in contrast to water displacing vessel has a wing and a mast underneath its' hull, we already focused on that earlier. In hydrofoil, a mast, wing, and a hull are all connected as a one robust system. The main component that experiences most of the loads is a hydrofoil's fixture, which connects the hull to a mast. The stresses that occur on a mast are transferred to an above-water body through the fixture, and in case its' failure, the wing and a mast disconnect from a hull, which virtually means that the whole system breaks. A compressive stress on a mast cross section is uniform due to the vessel's weight above the mast. The position of the maximum bending stress is indicated on the scheme.

Schematic overview is presented below:

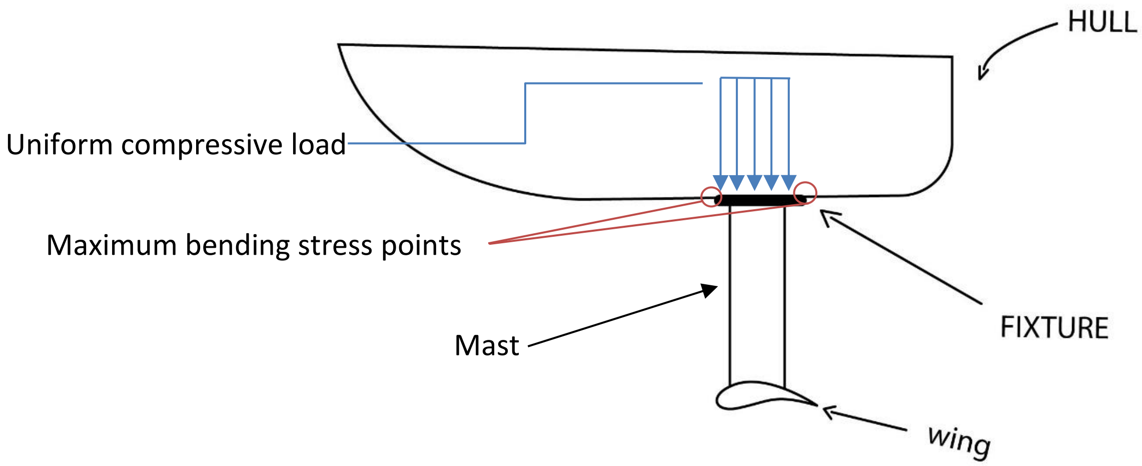


Figure 11. Schematic overview of a hydrofoil's components and loads (Pozhidaev,2021)

There are three operational modes for hydrofoil's motion.

1. Acceleration or water displacement mode

In this phase the vessel starts its' movement. Hydrodynamical forces on a wing are not yet creating enough lift to raise the hull of the water, and the water masses acting on a mast create only bending stress on it and on the fixture. This **might be** the moment of a maximum bending stress, the structure is not yet in hydrofoiling mode, and oncoming water streams are creating biggest amount of bending stress.

2. Hydrofoiling

In this phase the speed is big enough, and wings are generating lift to raise the craft out of the water and sustain a horizontal movement. In terms of loads, a new load is added to our system – a compressive load to a mast, that comes from a hull, that is now lifted out of the water. Previously we did not consider that factor since the hull was submerged in water.

3. Deceleration or breaking

The speed is decreasing, consequently the lift on the wings decreases too. The system starts to decent and a stress magnitudes become smaller. Compressive stays the same till the moment when the hull is submerged. Bending moment magnitude is in direct proportionality to a speed. Less speed means less drag, thus less bending moment.

3.1.1 Acceleration

Next free body diagram shows us the forces that are acting on a body during an acceleration phase.

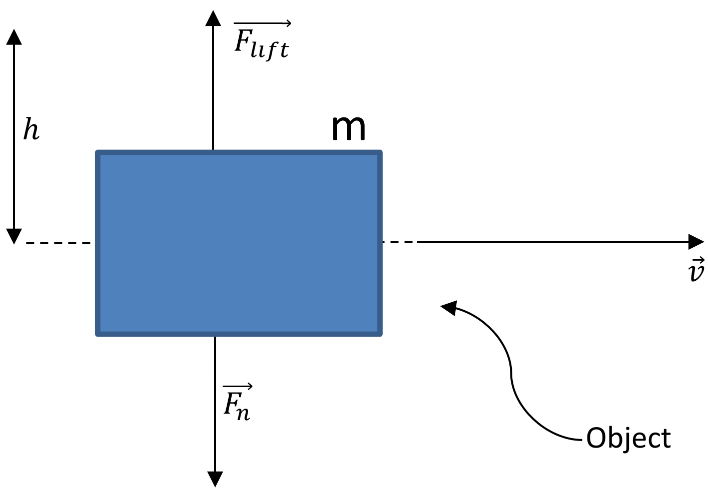


Figure 12. FBD of acceleration phase

Free Body Diagram for this mode (figure 12).

where,

m – vessel mass [kg]

$\vec{v}$ – velocity as the body accelerates [m/s]

$\overrightarrow{F_n}$ – Normal force [N]

$\overrightarrow{F_{lift}}$ – Lifting force [N]

As the body accelerates, it gradually starts to rise from the water surface due to the lifting forces which start to emerge on a foil, therefore normal force´s value $\overrightarrow{F_n}$ gradually increases, which means that effective weight of the boat also increases.

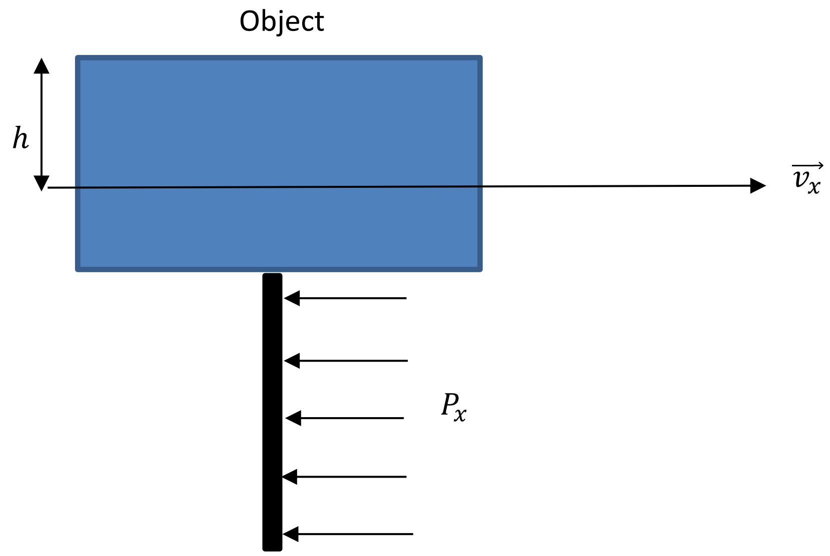
This means that when the vessel is completely submerged in the water its´ weight will be smallest, and conversely, when it is fully emerged, the weight will be maximum.

The lift produced by hydrofoil is equal to the effective weight of part which is above the water. The lift and the weight are both Y-directional.

The normal force $\overrightarrow{F_n}$ is balanced with the lifting forces produced by the foil. As the hull lifts from the water, $\overrightarrow{F_n}$ increases, so must the lifting force $\overrightarrow{F_{lift}}$ to keep the body balanced.

The normal force $\overrightarrow{F_n}$ is a function of height h , and the h ,in turn, is a function of $\overrightarrow{F_{lift}}$, which, in turn, is a function of $\vec{v}$

A different FBD for the same mode was created to show additional bending moment acting on a mast, as the body moves through the water. In this FBD we will specifically focus on a mast, as we will be considering the forces acting on it.



Where,

Figure 13. FBD with bending moment shown

$\overrightarrow{v_x}$ – velocity [meters per second]

P_x – pressure [Pascals]

h - height [meters]

The physics behind the mast could be calculated using a classical beam theory. Figures 14 and 15 illustrate the bending of a mast.

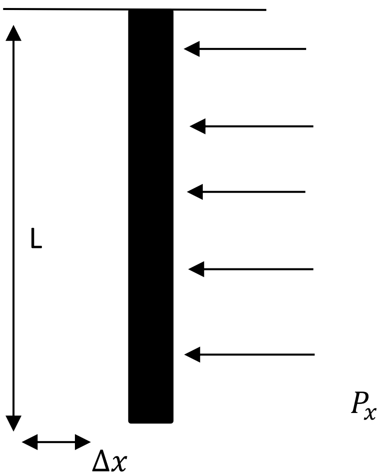


Figure 14.

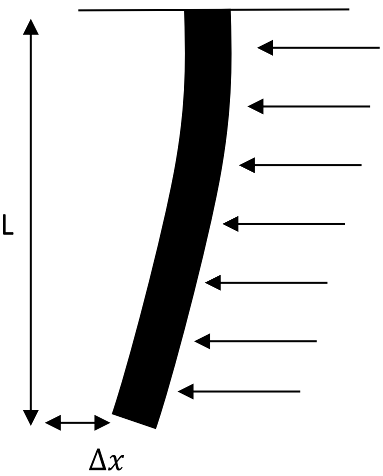


Figure 15.

The reason is why we have an additional x value is to represent the upward movement of the mast due to $\overrightarrow{F_{lift}}$. We will extract the x value from the L value to calculate the correct equation of pressure.

3.1.1.1 Load equations during acceleration

As the craft starts to move, different loads will occur on its parts.

The stress on the support of the mast is governed by following equations:

Bending stress

$$\sigma = \frac{Fl}{2Z}$$ *Eq.1* [5]

Where,

$\sigma - \text{stress at the support [Pa]}$

$F - \text{Load on the beam [N]}$

$l - \text{Length of the beam [m]}$

$Z - \text{section modulus of the cross} - \text{sectionon of the beam} \, [\text{m}^3]$

$$Z = \frac{I}{c}$$ *Eq.2* [6]

Where,

$I - \text{moment of inertia} \, [\text{kg}\cdot\text{m}^2]$

$c - \text{distance from neutral axis to the edge [m]}$

Which gives us:

$$\sigma = \frac{Flc}{2I}$$

The **deflection** Δx of the beam can be calculated with the following equation:

$$\Delta x = \frac{Fl^4}{8EI}$$ *Eq.3* [7]

Where,

F – Load $[\text{N}]$

l – length$[\text{m}]$

E – modulus of elasticity $[\text{Pa}]$

I – moment of inertia $[\text{kg}\cdot\text{m}^2]$

Therefore,

$$E = \frac{Fl^4}{8I\Delta x}$$

The third factor we must consider is the maximum strain. We will now derive the strain equation.

According to the Hooke`s law:

$$\sigma = \varepsilon E \qquad \textit{Eq.4}\ [8]$$

Where,

σ – stress [Pa]

ε – strain

E – modulus of elasticity [Pa]

Therefore,

$$\varepsilon = \frac{\sigma}{E} \qquad \textit{Eq.4}\ [8]$$

Inserting the previous equation for *E* and *σ* we get:

$$\varepsilon = \frac{Flc}{2I} \cdot \frac{8I\Delta x}{Fl^4} = \frac{4\Delta xc}{l^3}$$

3.1.2 Hydrofoiling

Now we focus on hydrofoiling mode physics.

For this matter the FBD is presented below:

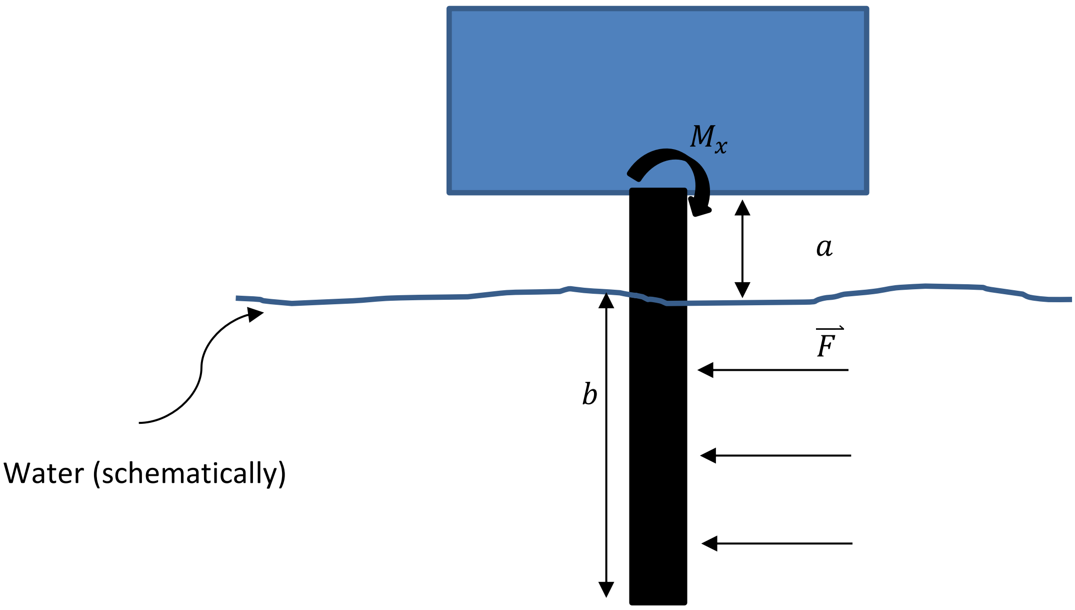


Figure 16. FBD of vessel in hydrofoiling mode

a = the part of the hydrofoil above the water

b = submerged part of the hydrofoil

l (length) = a+b

M_x – bending moment [Newtons·meter]

The hydrodynamic forces therefore will be acting only on part *b,* which is submerged. This means that the stress and strain that would occur on the root of the mast, would be a function of b.

However, as we accelerate, part *b* rises from the water, in other words, *b* becomes smaller. Knowing that, we see, that the more *b* rises, the less forces $\vec{F}$ is impacting the *b.* Simultaneously, the more we accelerate, the more hydrodynamic resistance the hydrofoil construction creates. We observe that:

$$\overrightarrow{F}\,(b;\ \overrightarrow{v})$$

3.1.2.1 Turbulent Flow

When the vessel moves, most of the time the hydrofoil is dealing with turbulent liquid flow. For the sake of simplicity, we will denote the hydrodynamic force as the constant K. This gives us:

$$\vec{F} = K \cdot \overrightarrow{|v|}^{n}$$

The n constant is present in the equation for the definition of the flow nature. When $n = 1$ the flow is linear, and the further we go from number one more we are dealing with turbulent flow.

When $n = 1$, the relationship between $\overrightarrow{v}$ and $\vec{F}$ will be linear.

The slope *k* will be the function of the exposed area.

The area, in term, will be equal to the $w \cdot b$

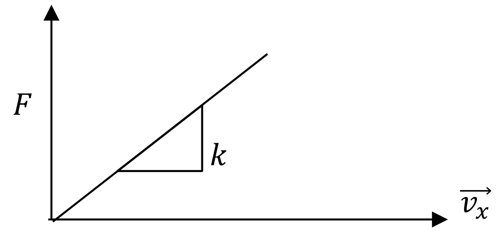


Figure 17. Correlation between Hydrodynamical resistance and velocity

Where,

F – hydrodynamic resistance [unitless]

$\overrightarrow{v_x}$ – horizontal velocity [m/s]

k – the slope

The equation for Area is:

$$A(\overrightarrow{v_x}) = w \cdot b(\overrightarrow{v_x}) \qquad \textit{Eq.5} \text{ [9]}$$

$$b = b_0 \cdot \left(1 - \frac{v}{z}\right) + b_1$$

The equation for b means, that the more the speed increases the less the b becomes but will never be equal zero, due to the fact that a whole craft cannot be physically out of the water. The b_1 constant is introduced in this equation to set the limit. b_1 practically represents the amount of a craft that stays submerged in the water, for instance, 0.15 meters.

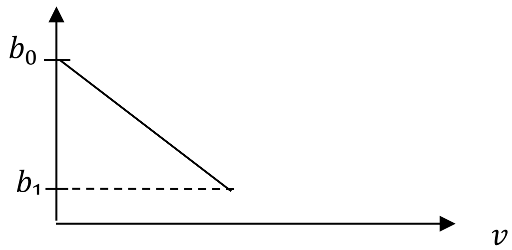


Figure 18. Correlation between exposed area resistance and velocity

We now extrapolate the previous equation and sketch a hydrodynamic resistance versus speed graph (figure 19) it would look as follows:

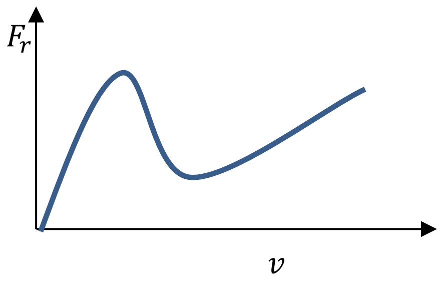


Figure 19. Hydrodynamic resistance versus speed

In ordinary vessel, the faster the speed, the bigger is a hydrodynamical resistance. In case of hydrofoil, as we increase the speed, the mast rises out of the water decreasing hydrodynamic resistance.

However, as explained on the equations previously, a part of the craft will always stay under the water, therefore inevitably creating resistance as we increase the speed.

3.2 Two types of loads

The theoretical breakdown of loads during hydrofoil operational modes allows us to state that during an on operation, the craft`s fixtures will mostly experience two types of loads:

1. Vertical compressive load.

The following load occurs due to a gravitational force, when the upper part of the vessel is rising from the water due to the lift produced by the wing. The load is acting in horizontal direction.

2. Bending load.

Unlike compressive loads, a calculation of bending loads requires more complex procedures.

To achieve desired results, we will utilize COMSOL software and finite element analysis.

3.3 Utilizing CFD and FEM for bending stress calculation

To be able to estimate the stresses on the fixtures, a simple analytical method is not enough. In our study we will use two powerful tools to achieve the results.

Computational fluid dynamics (later CFD) is a method which is used to study how a gas flow interacts with a solid objects. The studies are executed by a powerful software that utilizes a computational power of a PC. In our study we will use COMSOL. Upon completing the study, we can observe pressure distribution along the object.

Finite element analysis (later FEA) is a complex method of simulating physical phenomena with the help of computational power. Along with CFD we will use FEA to estimate the stresses on the body.

3.3.1 Reynold`s number

The Reynold's number or Re is a numerical ratio which is used in fluid mechanics to define the nature of a flow. The flow can we either turbulent or laminar. The number has no units. A *laminar flow* is a flow is one in which the fluid particles move in smooth layers, or laminas (Pritchard et al., 2015) [14]

Whereas the *turbulent flow*, is a flow in which the fluid particles rapidly mix as they move along due to random three dimensional velocity fluctuations (Pritchard et al., 2015)[15]

The higher is the Reynold`s number, the closer the flow is approaching to a turbulent.

The flow is considered laminar when Re is lowe than 2300, and turbulent when Re is above 2300) [15]

3.3.1.1 Calculation of Reynold`s number

The equation for calculating Re is following:

$$Re = \frac{\rho u \mathrm{L}}{\mu} \qquad \text{Eq. 6 [10]}$$

Where,

$Re -$ Reynold's number [unitless]

$\rho -$ fluid density $[\mathrm{kg/m^3}]$

$u -$ flow speed $[\mathrm{m/s}]$

$\mathrm{L} -$ characteristic linear dimension

$\mu -$ dynamic viscosity $[\frac{\mathrm{N \cdot s}}{\mathrm{m^2}}]$

3.4 Test Model

In order to see what is the maximum stress that appears on the mast at a given speeds a simple test model (figure 23) for COMSOL was created. This model does not represent an actual geometry of a mast, but rather serves as a platform that lets us investigate the correlation between the nature of the flow, speed and the stress occurring on the craft.

To set up our model we first select number of dimensions in our study. We select 3D study (Figure 20)

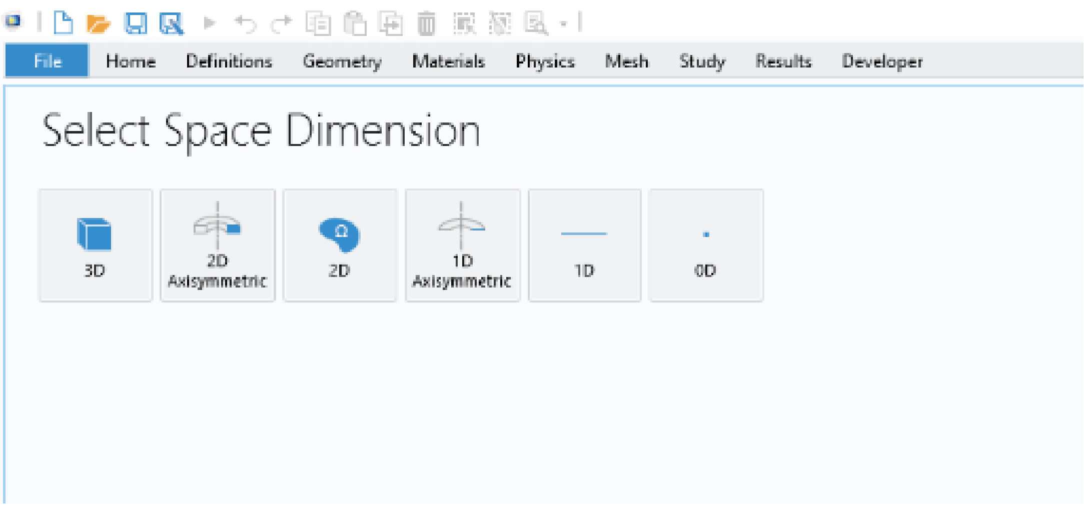


Figure 20.

Next, we would like to set a phystics scenario in which we are interested. In our case it is fluid-solid interaction with fixed geometry (Figure 21)

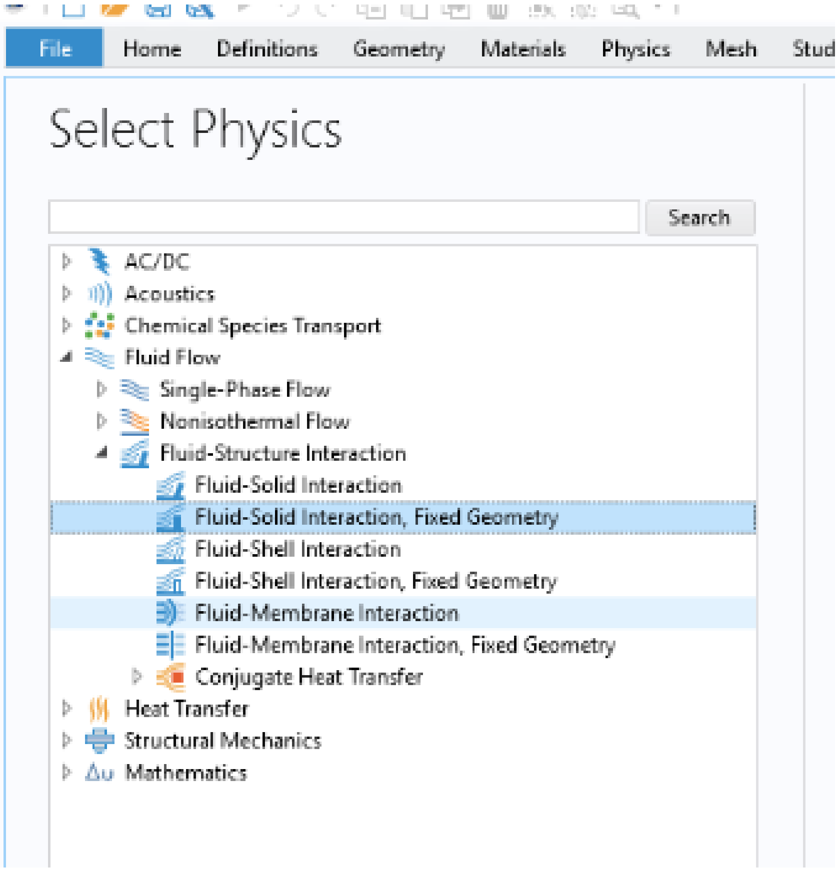


Figure 21.

Next, we select studies we would like to conduct. We will conduct two of them – first one, CFD study that gives us pressure field, and second, structural study that uses pressure field to calculate stress.

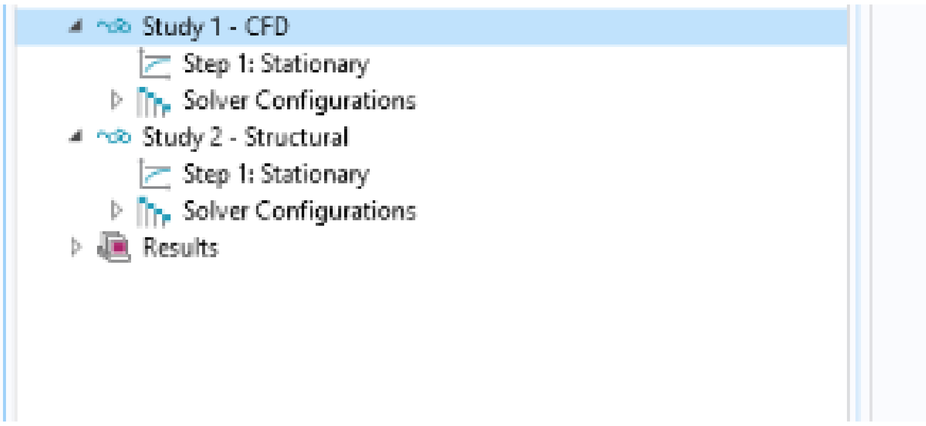


Figure 22. Two studies

Our test model would look as following.

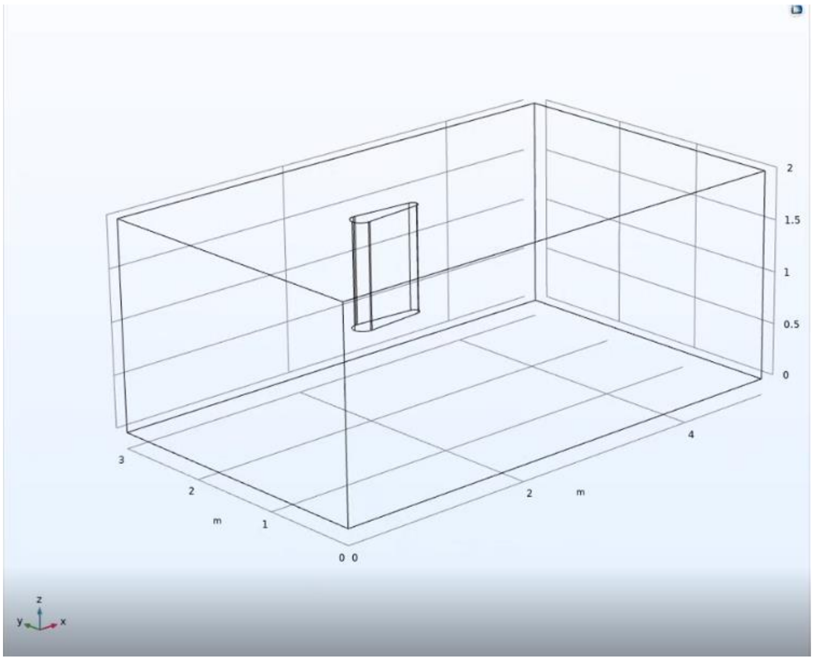


Figure 23. Test model

In order to observe the stress growth with the speed, we will run 8 independent analyses for the speeds from 2,5 m/s to the speeds of 20 m/s with 2,5 m/s the step width.
According to the setup, the mast is one meter high and fully submerged in the water. The boundary conditions are set so, that the object is only fixed by one side – the uppermost surface. All the other surfaces are not fixed.
The surrounding fluid is set to be a water with density of 1000kg/m^3.

3.4.1 Reynold's number for CFD analysis

Before we can test run our model in the software, we must decide what flow type we will be using – the turbulent or the laminar. This is a crucial moment, as the software considers these as two different studies
For this matter we will estimate an approximate Re for 5 m/s speed using the formula from paragraph 3.3.1.1.

The initial conditions for our system are:

Speed – 5 m/s

Chord length – 0,6 m

Dynamic viscosity – 0,001 $m^{-1}s^{-1}$

Density – 1000 kg/m^3

Therefore, Re for 5 m/s equals to:

$$\boldsymbol{Re} = \frac{1000\frac{kg}{m^3}\cdot 5\frac{m}{s} * 0{,}6\ m}{0{,}001\ m^{-1}s^{-1}} = 300000$$

The equation gives us 300000, which corresponds to a turbulent flow.

We observe a chaotic type of flow already on 5 m/s , so all the further simulations will be calculated with respect to a turbulent flow model, since it is not necessary to test the model at speeds lower than 2,5 m/s.

3.4.2 Pressure field and maximum stress results for 1-meter-long mast

The test is computed 8 times for 8 different speeds using turbulent flow. This will give us 8 results for the pressure fields.

1Upon completing first 8 runs we obtained the results for pressure fields (table 1 & figure 24).This knowledge is then used to calculate the maximum stresses for different speeds. The table with results is presented below:

Table 1 .Stress versus speed graph

Speed, m/s	Max Stress, MPa
2.5	0.00002
5	0.09
7.5	0.21
10	0.37
12.5	0.57
15	0.83
17.5	1.12
20	1.47

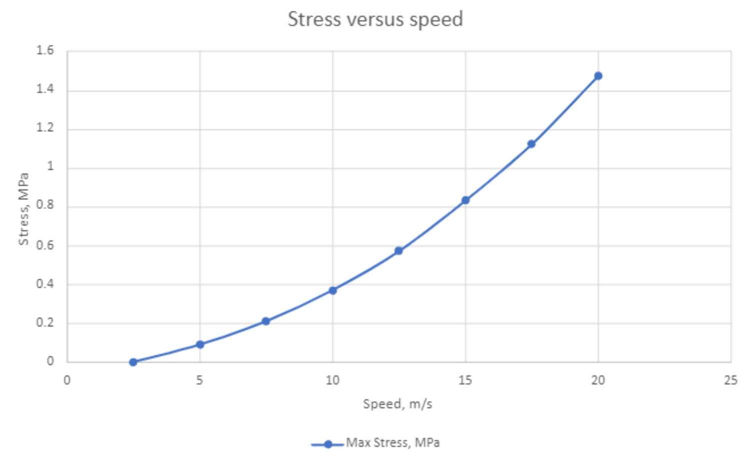


Figure 24. Maximum stress for different speeds

3.4.3 Pressure field and maximum stress for 0,5m long mast

The hydrofoil has a wing that, obviously, creates a lift. On certain speed, the lift force on the wing starts to create enough lift to start pushing the whole craft up. At that moment the mast of the craft begins to rise from the water, consequently the bending moment created by the oncoming hydrodynamical forces starts to decrease. Now we will study the case when the mast is submerged only to 0,5 meters in the water, to see how to stresses change in the structure.

We are using the same model, except it is shortened to 0,5m to simulate mast´s ascent from the water (figure 25)

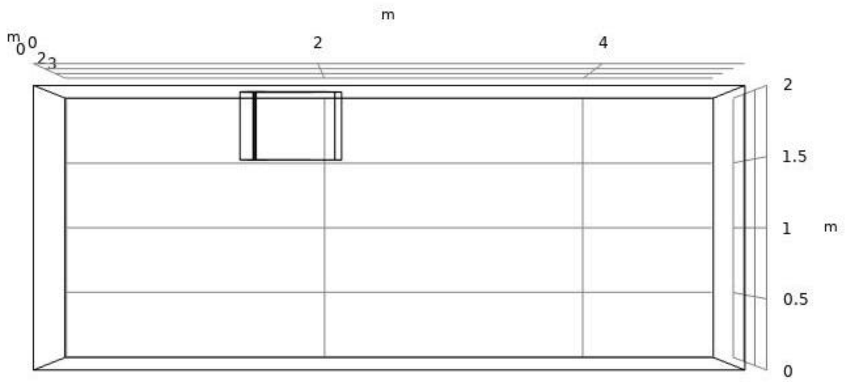


Figure 25. Mast simulation model. 0.5m submersion

We repeat the operations we performed with the fully submerged model. In another words, we run 8 different studies of this model with current speeds from 2,5 m/s to 20 m/s. The boundary conditions are exact same for this model as for the first, fully submerged model. We receive the following results for maximum stress versus speed. The diagram presented below (Figure 26)

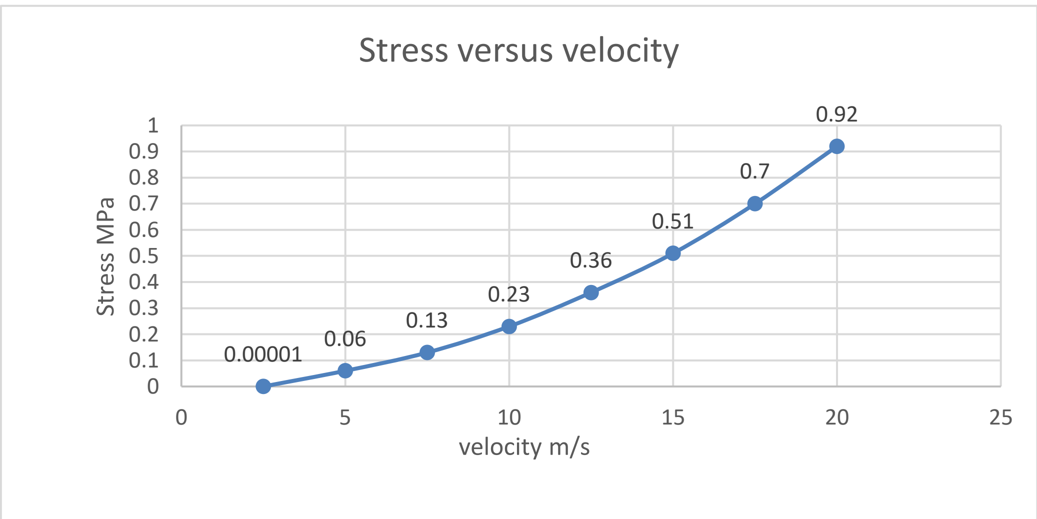


Figure 26. Stress vs velocity

Figure 27 and figure 28 represent maximum stress and pressure field distribution at the speed 5 m/s and serve as illustrations.

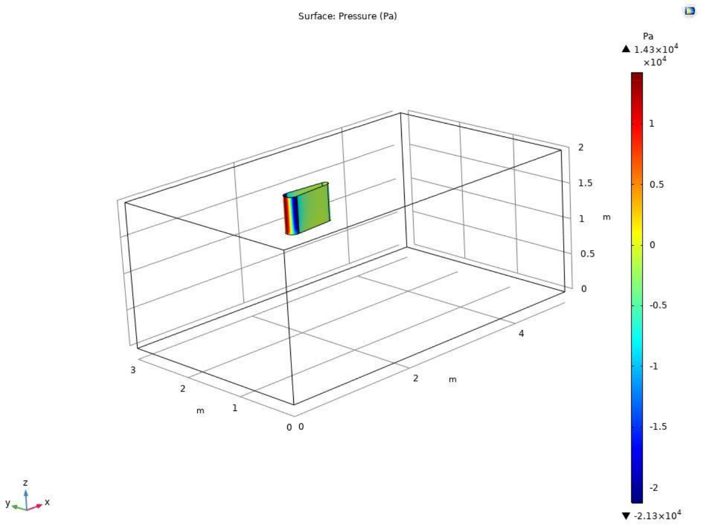


Figure 27. Pressure field distribution at 5 m/s

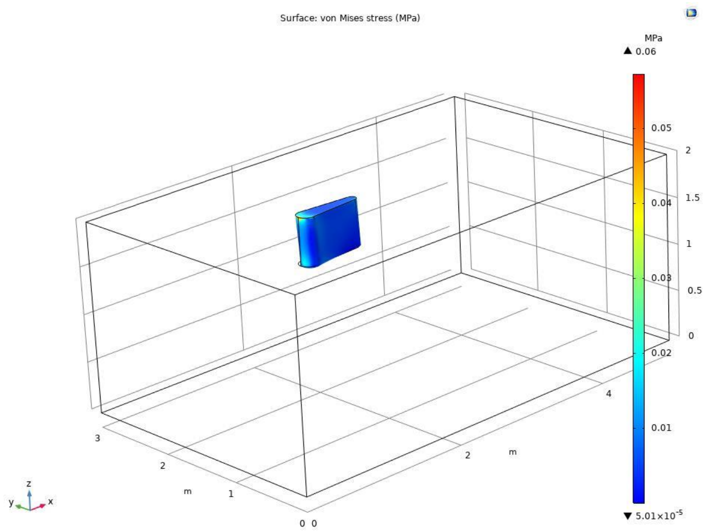


Figure 28. Maximum stress at 5 m/s

On the chart below we can see the comparison between fully submerged mast and mast which is submerged on 0,5 meters into the water. X-axis represents maximum bending stress in the structure, Y-axis represents speed. The speeds are varying from 2,5 m/s to 20 m/s.

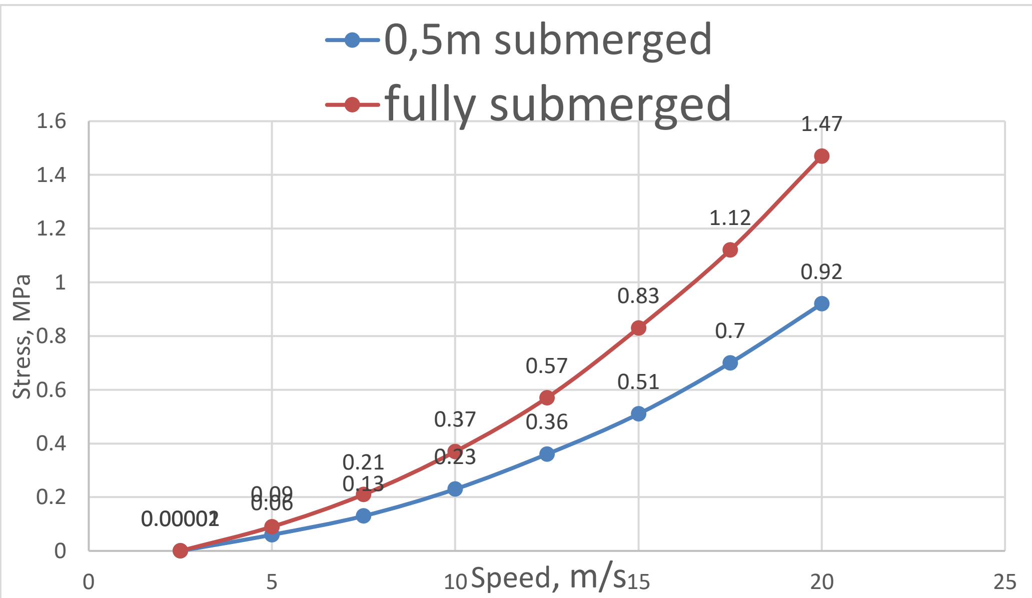


Figure 29. Stress vs Speed comparison between fully submerged mast vs 0,5m submerged mast.

3.5 Wing

Previously we assumed that the maximum bending stress will occur when the craft is in a water displacement mode, before the moment its' hull lifts out of the water.
At that moment the speed is not big enough to start lifting the hull and mast out of the water, therefore, the whole mast is submerged and all the water mass that is moving towards the mast is creating biggest amount of stress.
We would like to know the exact speed at which the vessel starts to lift out to pin-point the correct stress magnitude from our previous graph.
To do that, we must add to our model a **wing.**
The hull, obviously, has its' own mass. In our study we will take an existing speed-boat's hull which weight is roughly equal to 1500 kg. Hull's technical data can be found in appendix.
At a certain speed the wing will generate enough lift which is acting upwards, to compensate the hull's mass and the vessel will rise.
That speed depends on a variable such as:

- Lift coefficient C_l
- Surrounding fluid density
- Wing surface are v

3.6 Lift off speed

According to the lift equation, lift force equals to:

$$L = \frac{1}{2} C_l \rho v^2 A$$ *Eq. 7 [11]*

Where,

$L -$ Lift force [Newtons]

$C_l -$ lift coefficient, [unitless]

$\rho -$ fluid density, [kilograms/meters^3]

$A -$ wing surface area , [meters^2]

$v -$ velocity, [meters/second]

3.6.1 Lift coefficient calculation

Lift coefficient is a unitless quantity that determines an ability of a given airfoil to generate lift on a given angle of attack. Lift coefficient is defined specifically for each airfoil. In our study we are going to use an airfoil with already calculated and known C_l. A Naca (National Advisory Committee for Aeronautics) database includes vast variety of airfoils, which are well-studied.

We will use NACA 4415 airfoil in our study (figure 30)

The foil lift coefficient alters with the angle of attack and Reynold's number [17]. In our study we are going to use 0 degrees angle of attack to keep the model simple.

The figure 31 shows us the correlation between angle of attack (x axis) and lift coefficient (y-axis). Reynolds number for the following graph is 200000.[12]

We can observe that the lift coefficient at 0 degrees of angle of attack equals to **0.5**

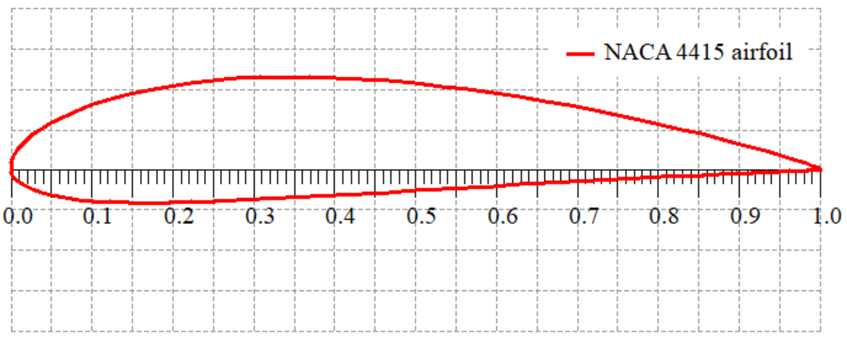


Figure 30. Wing Profile

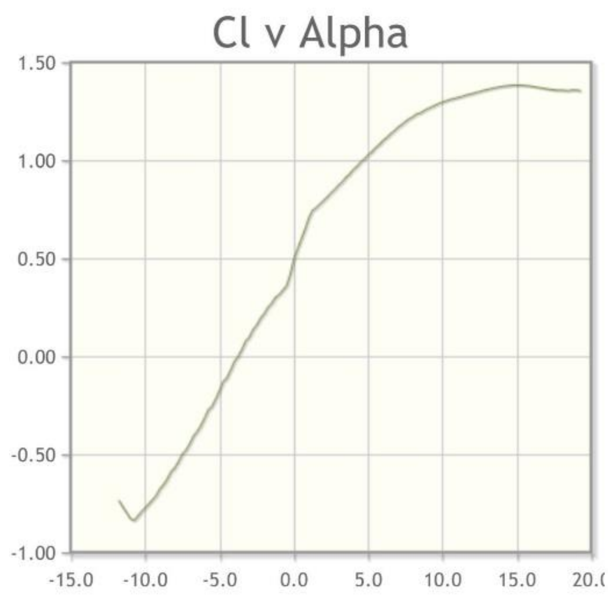


Figure 31. Lift coefficient vs angle of attack

3.6.1.1 Wing surface area

The wing surface area is a total wing projected area, as if we were looking at the wing from top-down view.

In our study, the wing will be 2 meters wide and 1 meters long, which gives us **2 square meters of surface area**.

3.7 Calculating lift-off speed

To calculate a lift off speed, we must modify an equation from paragraph 3.6, so that we could see a minimum speed that will be needed to start to lift up the vessel.

The original equation shows how much lift in the wing will generate at a given speeds, but we already know how much weight is needed to be lifted, and that a vessel mass – 1500 kg or 14709 Newtons. We can insert this quantity in the equation, rearrange it, and obtain a minimum liftoff speed for given parameters.

Lift equation from section **3.6:**

$$\mathrm{L} = \frac{1}{2} \cdot \rho \cdot v^2 \cdot C_l \cdot A$$ *Eq. 7 [11]*

Rearranging for v:

$$v = \sqrt{\frac{2L}{C_l A \rho}}$$

We obtained an equation that gives us a minimum lift-off speed for our wing.

We know,

$$\rho = 1000 \frac{\text{kilograms}}{\text{meters}^3}$$

$$C_l = 0.5$$

$$L = 14709 \text{ Newtons}$$

$$A = 2 \text{ meters}^2$$

Therefore,

$$v = \sqrt{\frac{2 \cdot 14709\ N}{0.5 \cdot 2\ m^2 \cdot 1000\frac{kg}{m^3}}}$$

$$\boldsymbol{v = 5,42\ m/s}$$

We can see that the lift off speed for our vessel is 5,42 meters per second.

3.8 Maximum stress at liftoff

As we learned previously, the craft will start to liftoff once the speed reaches 5.42 m/s. However, until this speed is reached, the mast remains fully submerged and up until the moment of liftoff, by our assumption made in section **3.5**, the stress is maximum. We now must justify or refute our assumption.

A method that we are going to use in our study relies on a superposition of a CFD. Normally, to study stress peaks in a simulated environment, a complex model with many variables is created. Those variables include time dependent model, speed-depended lift and bending stress models. Such a model is complex and, if all the variables are set correctly, precise. However, in our case study, we can evade unnecessary calculations by taking out factor that can be excluded without any consequences on a final result.

This factor is stress development study after the moment of a lift off till the moment of a maximum simulated speed. We know that the wing starts to create enough lift on a speed higher than 5.42 meters per second. We also know that before that speed the hull stays submerged and no compressive load on a mast is exerted. At the moment of a lift off, since buoyant forces no longer balance the weight of a hull, all the weight focuses on a cross section of a mast and a fixture. We would like to note, that this weight does not increase, it will stay the same all the time, so compressive load is constant.

Simultaneously, at the moment of a lift-off, the bending moment on a mast reaches its' maximum values, since bigger part of a mast is still submerged, and oncoming water streams render most amount of bending stress.

As the system accelerates, compressive load stays constant, however bending load decreases, due to the fact that increased speed creates increased lift, thus pushing the craft upward, leaving less mast's surface area submerged, which, in turn, means that less bending stress in created in the mast.

This virtually means that the maximum combined stress on a fixture might be at the moment of a lift off, since exactly at that moment bending stress and compressive stress reach their maximum values.
Knowing that, we simply can omit simulation of a phase after lift-off and till the maximum speed moment, since we know that compressive stress in any case stays the same, and bending stress decreases.

3.9 Mast modification

The original mast model from paragraph 3.4 was made merely for illustrational purposes, and had no scientifically proven background. Knowing that, an author decided to use an existing symmetrical airfoil form NACA, and the model NACA 16009 was chosen (figure 32) This airfoil is thin, sleek, and long, so hydrodynamical forces will be smaller. The length of the mast, if measured by the center line from leading to trailing edge, is exactly 1 meter [13]. The height of a mast from top to bottom is 1 meter. We will now modify our COMSOL model and insert there a modified mast model.

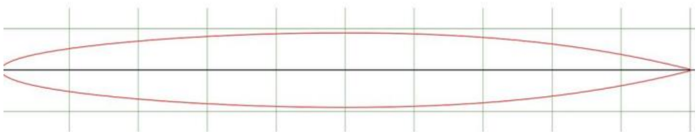


Figure 32. New mast profile

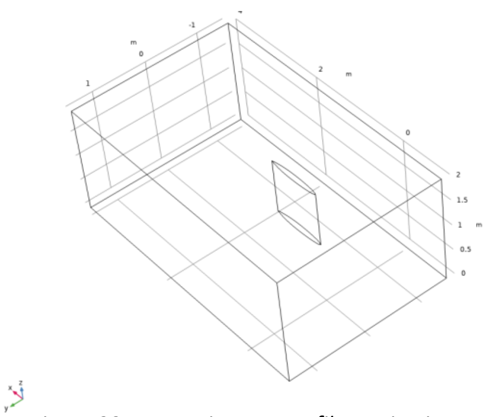


Figure 33. Isometric mast profile projection.

However, before we can proceed to a further investigation of an assumption made in paragraph 3.8, we must conduct new stress simulations for new mast model. We now expect significantly lower stress magnitudes due to modified design. As before, we will conduct 8 simulations for speeds varying from 2,5 m/s to 20 m/s. And as previously there will be 2 mast positions – fully submerged and raised.

3.10 New simulations

We start from running a simulation for fully submerged mast. The simulations are ran using turbulent model flow. We are especially interested in the point where speed reaches 5.42 m/s, since it is presumed point of maximum stress.

After completing 8 simulations in COMSOL, we obtain following data:

Table 2. Data, Submerged mast

FULLY SUBMERGED	
speed m/s	stress MPa
20	0,96
15	0,54
10	0,24
7,5	0,13
5,42	0,12
5	0,06
2,5	0,01
1	0,00283

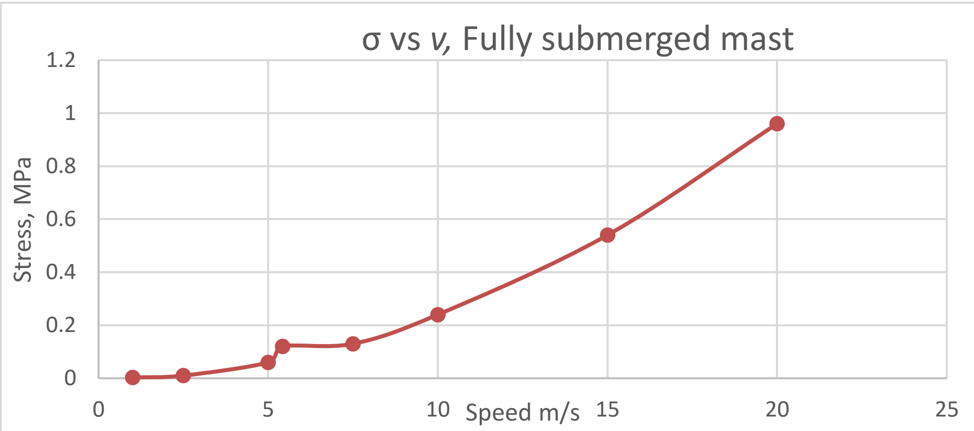


Figure 34. Submerged mast data

We can see one particularly specifically interesting moment on this graph. The stress raises gradually on 1m/s to 5 m/s region, and suddenly, on a 5,42 m/s we see a rapid raise in stress magnitude. This is exactly the moment when transition from water displacement mode to hydrofoiling occurs. It is a point of maximum dynamic pressure.

The orange graph represents a simulation for fully submerged mast, and stress continues to rise, however, this happens only in simulated environment. In practice, after lift-off speed, the mast starts to rise and stress gradually decreases. This statement will be discussed more specifically on a next page.

Now we evaluate a simulation result for raised mast and compare the data to submerged mast results.

On table 3 we can clearly see that the maximum stress at 20m/s in raised state is lower that than the stress at 5,42m/s at submerged mast state. This practically means that the maximum stress magnitude, indeed, is a point at 5,42 m/s of take-off. Once that speed is reached, the craft starts to rise and we switch from orange (submerged) graph to blue (raised) graph, and maximum stress that we will ever achieve in raised state, as mentioned before, is 0,08 MPa at 20 m/s.

Tab.3 Data for raised mast

Speed m/s	Stress, MPa
20	0,08
15	0,04
10	0,02
7,5	0,01
5	0,00683
2,5	0,00116
1	0,00024

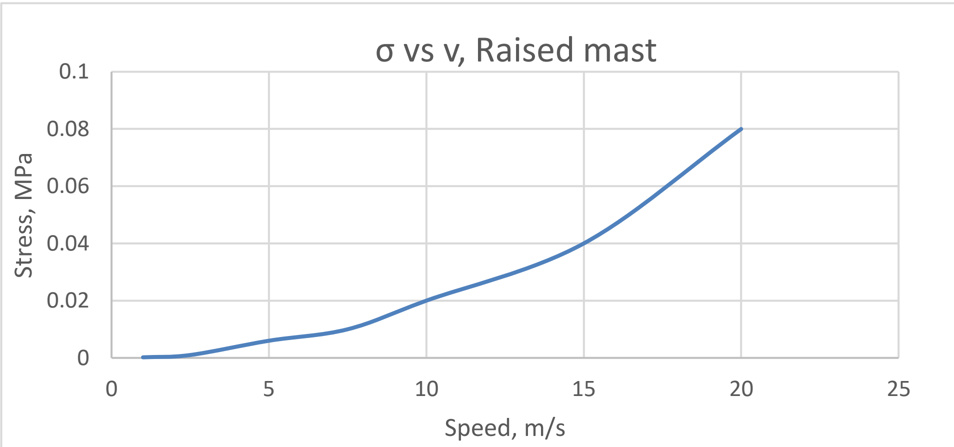


Figure 35. Stress graph for raised mast

We combined two graphs, in other words, a data for *x* and *y* axis up until v ≥ 5,42 m/s is taken from orange (submerged mast) graph, and after v < 5,42 m/s the data for both axes s taken from blue graph. Combined graph for stress versus speed looks as following:

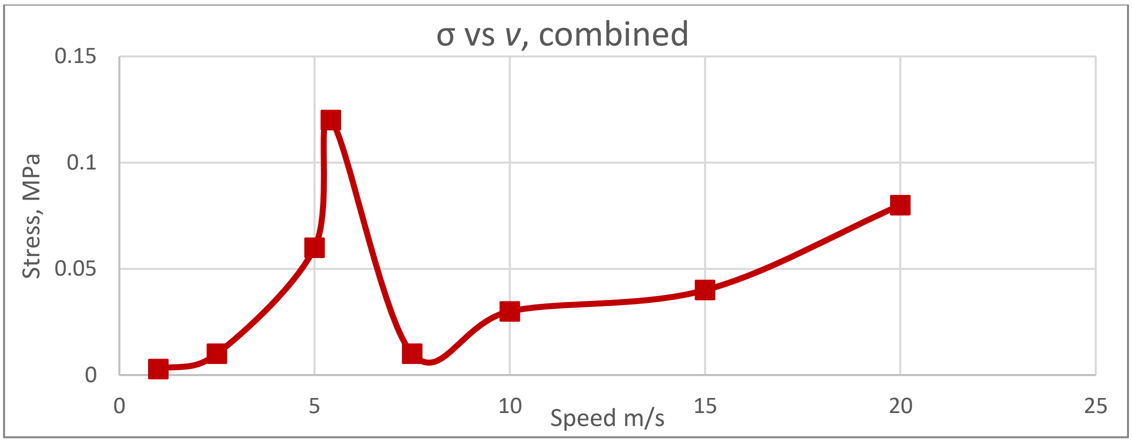


Figure 36. Combined graph for stress vs speed

We observe exponential stress growth until 5,42 m/s is reached. And instantly after we see a rapid decent of stress magnitude, since in that exact moment the vessel begins to hydrofoil. According to that, we can deduce, that the maximum operational stress occurs at speed of 5,42 m/s.

3.10.1 Adding a compressive load.

A purpose of a hydrofoil is to lift an upper part of a vessel from the water. We also stated that the vessel, obviously, has its' own mass that we determined to be 1500 kilograms, or 14709 Newtons. This force acts straight downwards and compresses the mast of a hydrofoil. Knowing that, we must add to our computer model a new constant - vessel mass. Previously our model considered only bending stress from coming water streams.

On a data table below, we can see the speed and a corresponding maximum combined stress calculated by a software. We observe that the stress magnitude dramatically elevated.

Peak stress magnitudes are located on the edges of the mast.

This specifically means that those parts of a fixture must be sturdy enough to withstand a maximum stress at any given moment. Knowing the possible points where the fracture is likely to happen, we can prevent it, by strengthening specifically those points of a fixture.

Table 4. Combined maximum stress for different speeds

Speed, m/s	Stress max, MPa (compressive + bending)
5.42	0.86
7.5	0.39
10	0.45
15	0.46
20	0.47

We would like to emphasize, that we simulated a compressive load and bending moment only after lift-off speed (5.42 m/s), since hull´s mass does not create any compressive load while the vessel is submerged. Compressive load starts to act only after an actual lift off, when the gravity takes a place in its' fullest.

4. RESULTS

4.1 ACCELERATION PHASE

An acceleration phase is a phase from the beginning of a vessel's movement, till the moment of a lift-off. The peak stress at an acceleration phase has observed to be 0.86 MPa and occurs at the moment of lift-off. Maximum bending stress was 0,12 MPa at the speed of 5.47 m/s. The below figure demonstrates the peak stress distribution in the fixture (combined – bending & compressive) We can clearly identify the points with most stress – those are the corners of an airfoil if looked in XZ plane. Figure 37 demonstrates this finding

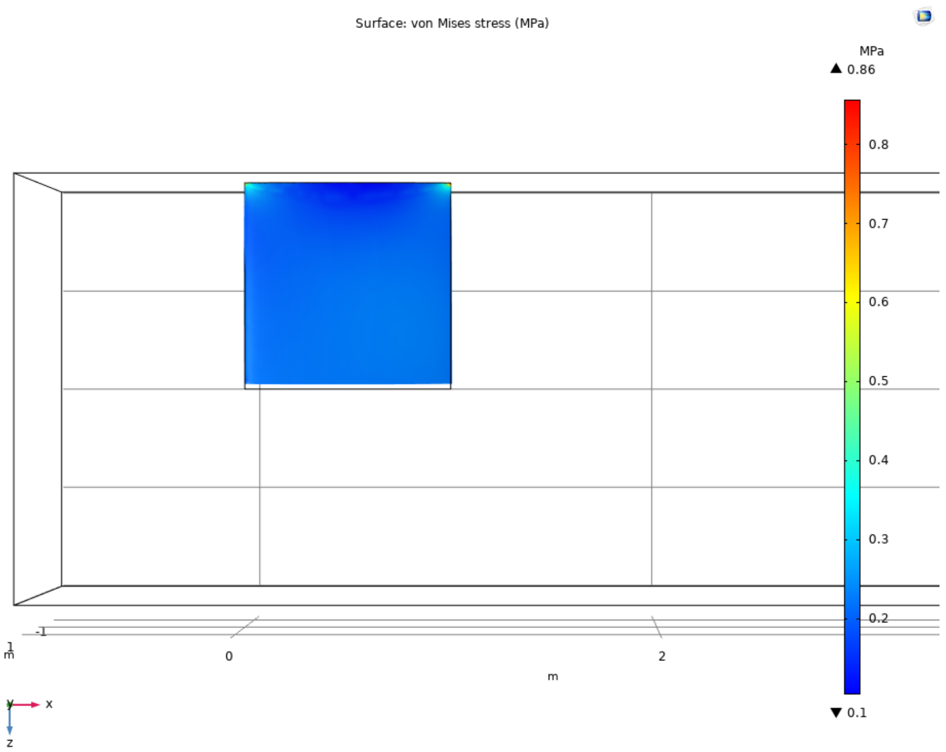


Figure 37. Peak stress magnitude at acceleration phase. Submerged fixture and mast. Moment of a lift-off.

$v = 5{,}42\ m/s$

4.2 Hydrofoiling phase

The greatest speed set in our simulations was limited to 20 meters per second, or 72 kilometers per hour. This is an optimal to maintain during hydrofoiling phase – a perfect balance between speed, fuel consumption and drag.

The results have shown that the greatest stress occurring in the fixture equals to 0,47 MPa at $v = 20\frac{m}{s}$, which proofs our theory about the greatest stress magnitude occurring at $v = 5.42\frac{m}{s}$. As well as in acceleration phase, the biggest stress magnitudes are observed on the corners of an a mast.

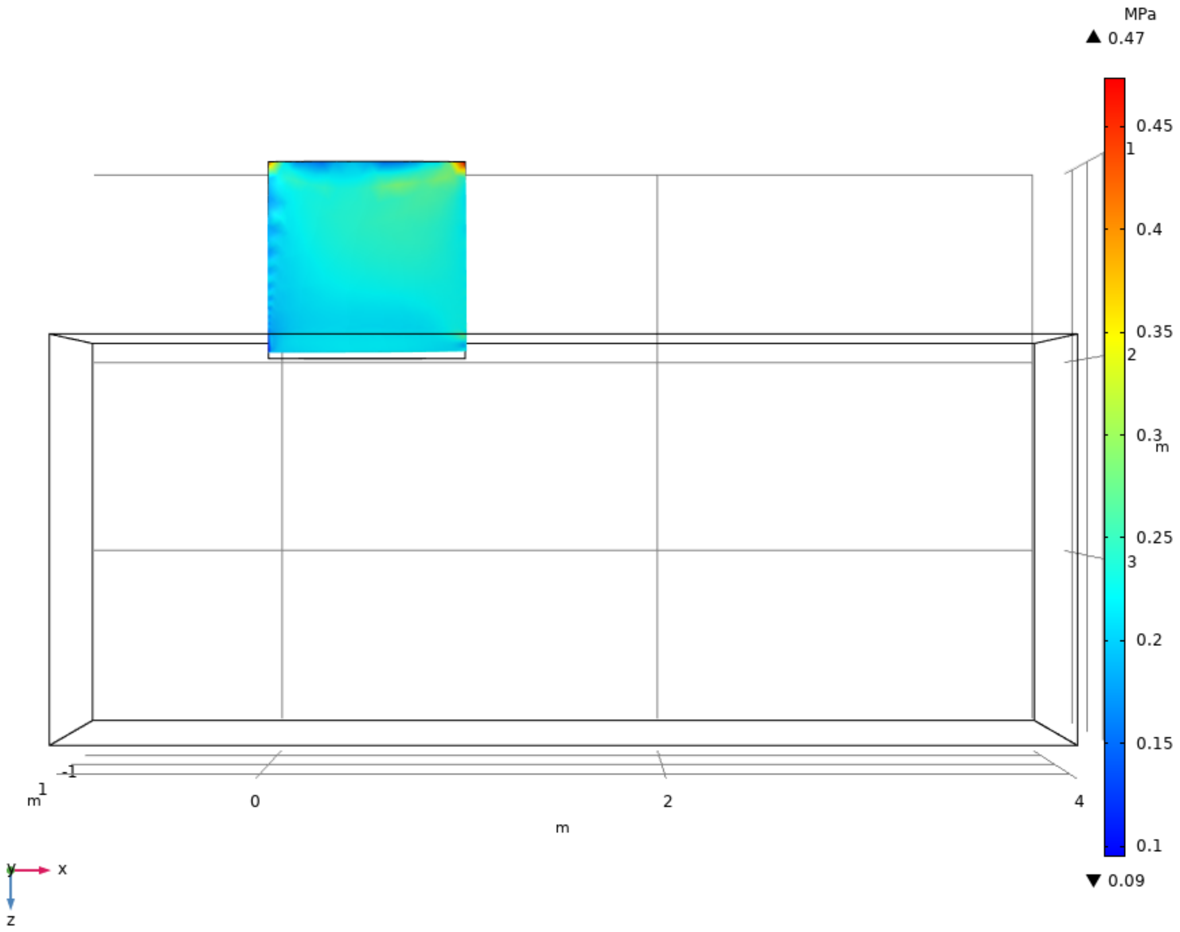


Figure. 38 Maximum stress magnitude at $v = 20\frac{m}{s}$

4.3 Deceleration phase

A deceleration phase is a virtually the same as an acceleration phase in terms of loads and stresses, however the stress reaches its' maximum values when the hull starts to contact a water surface at $v = 5{,}42\frac{m}{s}$.

The maximum stress at deceleration phase equals to 0,86 MPa at $v = 5{,}42\frac{m}{s}$.

5. DISCUSSION

The main idea of this research was to study the peak stress magnitudes on a fixture loads of a hydrofoil. As stated before, simulating an airfoil (fixture) moving in a fluid environment is a challenging task, requiring a powerful engineering tool such as COMSOL. During the study, more than 100 simulation iterations were conducted, and several airfoils were put into the test. The importance of determining the peak loads is crucial, as it impacts the safety of passengers onboard.

In the theoretical part of research, we focused on a perspective of calculating the bending stress with the help of simple equations, which eventually turned out to be impossible, since the problem needs to be considered more profoundly with the help of CFD software. After theoretical part of the work, we concluded that the greatest stress magnitude might be at the moment of a lift-off, which was later proven to be a correct presumption.
To calculate a lift-off speed, we used a rearranged lift equation that is applicable to any air-foil. Lift-off speed depended on variables such as lift coefficient, surface area of a wing, density of a fluid and others.

During our simulations in COMSOL we first calculated the pressure field at different speeds and based on that knowledge we were able to calculate a stress magnitude at specific ve-locity, which eventually gave us what we were seeking for – peak stress magnitudes.
A wing profile selection is also an important factor to consider. Depending on it, a lift-off speed varies, since different profiles have different lift coefficients. We could have picked up a thicker wing profile, which would give us a bigger lift coefficient, but this comes with significant drawback – an increased drag, thus increased bending moments, and increase in overall stress. After comparison between several options of profiles, we decided to use NACA4415 airfoil. All the simulations were running with respect to a turbulent flow nature. The research covered three stages, or modes of operation – acceleration, hydrofoiling and deceleration. For each mode we obtained a corresponding peak stress data.

However, the results we obtained can not be called accurate due to two factors.
First one is a nature of a flow we used in a simulation. A turbulent flow is known to be extremely chaotic, often rendering stress results to be inaccurate. As we discussed earlier, we were not able to use laminar flow model due to high Reynold's numbers.
There were two stress types we were interested in calculating – compressive stress and bending stress. A calculation of compressive stress is relatively simple – we use classical compressive stress formula:

$$\sigma = \frac{F}{A}$$ *eq. 8 [19]*

$\sigma -$ compresive stress [Pa]
$F -$ force [N]
$A -$ area [mm^2]

Since we know the mass of the hull, a cross-sectional area of a mast, we can calculate compressive load on a fixture even by hand. However, simultaneously there is a bending load on a fixture, which we can not calculate using simple equations, due to its' 3 dimensional nature. To calculate this type of stress we have to apply to CFD and FEA , which, in combination with turbulent flow model and low mesh resolution (we used normal mesh size in our study) can not be acknowledged trustworthy.
An author only had access to a school computer, that do not have enough computational power to run simulations on extremely fine mesh sizes, or in case we would run such a simulations on a school computer it lasted for days.

5.1 Materials selection

We theoretically studied maximum hydrofoil fixture loads and obtained theoretical data. Stress magnitudes would allow us to identify most suitable material for fixtures.
For smart material selection we use Ashby plot to identify most suitable material for our fixture.
Requirements are following:

1. less than 3000 $\mathrm{kg/m^3}$ density

The mast has to be made out of stiff and relatively lightweight material in order not to create too much excess weight. Otherwise, in extreme cases, the mass of the mast could simply be more than the lift force created by the wing, so the vessel would never hydrofoil.

2. High compressive strength.

The material must deal with compressive loads from the hull´s mast

5.2 Ashby plot

An Ashby plot is a data sheet that is used to pick up correct material in accordance with one's needs. It is used in material selection process.

On X-axis we see density of a material, and on Y-axis we see a modulus of elasticity.

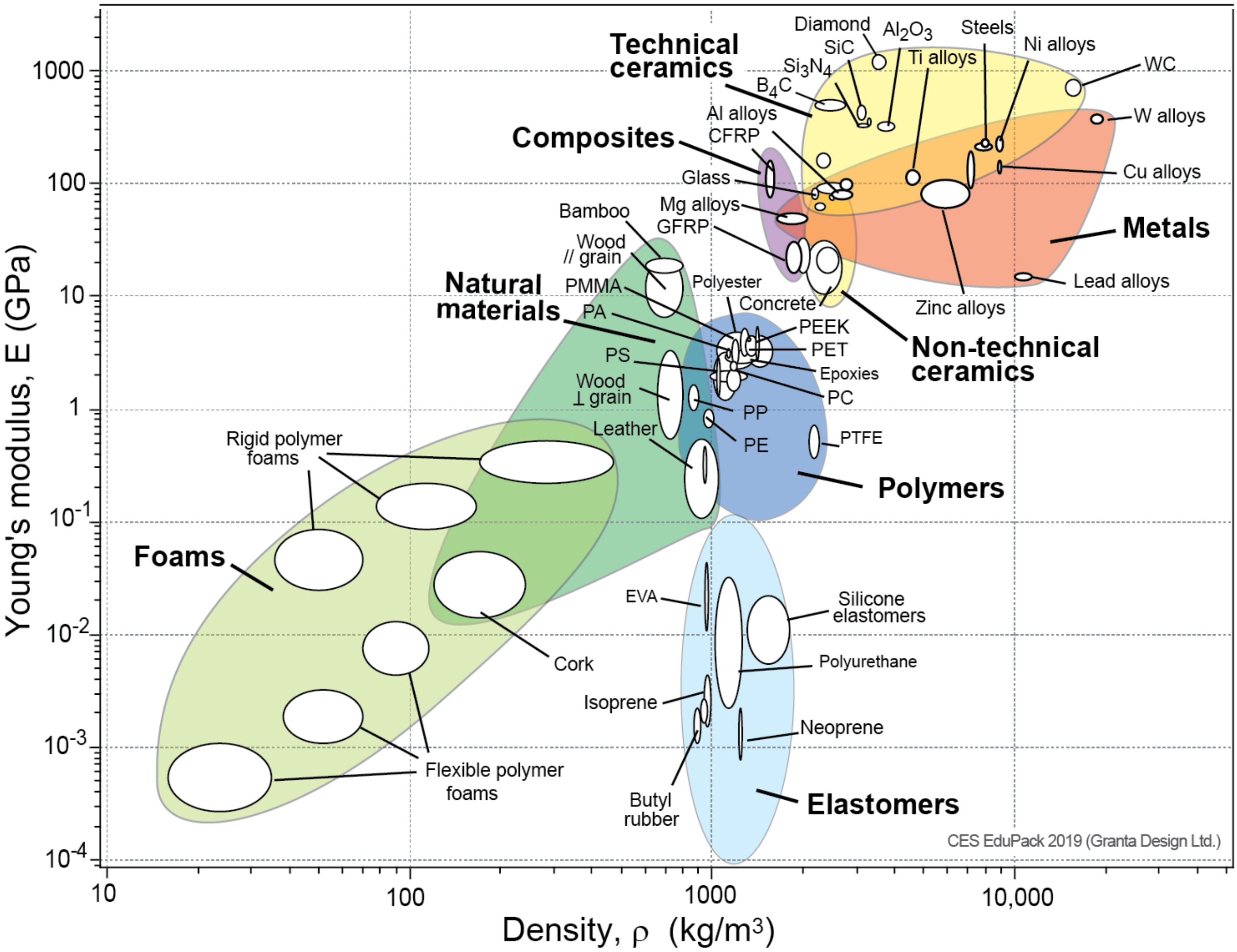


Figure 38. Ashby plot. (2020 Granta Design) [26]

Based on our requirements, we see than Alumiminun alloys and composites fit the best for our purposes.

6. CONCLUSION

The study revealed that the greatest stress which the fixture would experience equals to 0.86 MPa, occurring at the moment of a lift-off, during an acceleration phase, at the speed of 5.47 meters per second.

While hydrofoiling at the speed of 20 meters per second, a peak stress shown by simulations equals to 0.47 MPa, which is significantly lower than the peak stress during lift-off.
An airfoil design of both mast and a wing make a significant difference in terms of drag and stress. In the first version of the mast profile, discussed in chapter 3.4, we witness that the stress, at 20 meters per second equals to 1,47 MPa. A streamlined version of a mast profile, discussed in chapter 3.9 shows a significant improvement - 0,96 MPa while moving at the same speed of 20 meters per second, which is almost 35% less stress in comparison to the first version. The reader might notice that latter stress magnitude for a mast profile is greater than stated earlier maximum stress magnitude of 0,86 MPa. This is due to the fact that we forcefully held the model (the mast) in the simulation under the water to see how the profile acts when fully submerged. In reality, the model would already be lifted out of the water at lift-off speed, so no stress greater than 0,86 MPa would emerge.
We would like to summarize our work by answering the questions that were asked in the begging of our work.

Question:

What peak loads occur in the fixture during an operation modes?

Answer:

The peak load during an acceleration phase equal to 0,86 MPa, and this is the greatest load a hydrofoil would experience during an operation. This is combined bending and compressive stress that occurs in the upper part of a leading and a trailing edge of a mast.

Maximum bending stress in a fixture observed to be 0,12MPa.

The stress gradually increases as the vessel gains the speed. Once a particular speed of 5.47 m/s is reached, the craft lifts-off due to a sufficient lift on a wings, allowing for a rapid deterioration of a stress magnitude. The stress, however, continues to rise with the speed and reaches 0,47 MPa when the vessel moves at 20 meters per second.

However, these calculations cannot be fully trusted due to the factors we discussed in section 5 – turbulent flow nature and low mesh resolution.

6.1 Future research

Current work focused solely on the peak stresses in hydrofoil structure, however, this knowledge paves the way for the future research in hydrofoil structural mechanics. An individual who might be interested in development of a more efficient, rigid and lightweight hydrofoil, might take a results of current work as a starting point. This is applicable in, for instance, hydrofoil racing boats.

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8. APPENDIX

Test hull used in the simulation corresponds to a dry weight of a following speedboat [online] Available at: https://s3.amazonaws.com/regalboats-dev/wp-content/uploads/Reduced_RegalBoats-PIG-2022-singlepages-color.pdf

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REGAL

Boat	Regal 21 OBX
Engine(s)	Yamaha 200 Y4200XB
Test Date	5/13/2017

Regal 21 OBX

Length Overall	21' 1"
Beam	8'6"
Dry Weight	3224 Lbs
Fuel Capacity	40 Gal
Weight as Tested	4500 Lbs

Yamaha 200 Y4200XB

Horsepower	200
Propeller	Yamaha Reliance
Pitch	15

Performance Data

RPM	MPH	GPH	MPG
1000	4.2	0.8	5.25
1500	6.3	1.3	4.85
2000	7.4	2.1	3.52
2500	8.3	3.3	2.52
3000	12.1	4.5	2.69
3500	22.7	5.5	4.13
4000	27.7	7.3	3.79
4500	31.6	9.0	3.51
5000	36.9	12.3	3.00
5500	41.1	15.2	2.70
6100	47.1	20.3	2.32

0-30 MPH 7.4

NOTICE TO CONSUMER

The information and data contained in this performance report is approximate and subject to many different factors and variables. It is provided as a guideline only and should not be relied upon as representative of actual performance. Your boat's performance may be different than the information contained in this performance report due to various factors, including your boat's actual weight, wind and water conditions, temperature, humidity, elevation, bottom paint, boat options affecting wind/ water drag and/ or boat weight, and operator ability.

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