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Variable camber hydrofoils in oscillating hydrofoil propulsion

Development of a prototype and a efficiency test setup

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Abstract

Flapping Foil is an ongoing development project at NTNU Technology Transfer working on a new way of propulsion for boats. Their goal is to eliminate two of the biggest issues with boats today, the low efficiency of boat propellers and the high friction created when moving in the water surface. Their solution to these problems is a hydrofoil propulsion system that will in addition to propel the boat more efficiently also lift it up out of the water reducing friction.

This master thesis has in collaboration with Flapping Foil looked at the possibility of using a curving hydrofoil for the propulsion system instead of a more traditional hydrofoil with a flap attached to it's rear end. There have been two objectives of this, to develop a prototype for this kind of hydrofoil and to create a test setup for comparing the prototype to a traditional hydrofoil.

Unfortunately because of a failure in an electrical component vital to the test rig no data has been collected, however all planning is completed and testing is ready to be done should the component be replaced. In addition to this a working prototype for a curving hydrofoil has been constructed.

Sammendrag

Flapping Foil er et pågående utviklingsprosjekt ved NTNU Technology Transfer som jobber for å utvikle et nytt fremdriftssystem for båter. Målet deres er å eliminere to av de største problemene med båter i dag, den lave virkningsgraden som propeller har og den høye friksjonskraften man må overkomme for å bevege seg i vannoverflaten. Måten de har tenkt til å løse disse problemene er ved hjelp av et fremdriftssystem som benytter hydrofoiler. Systemet driver båten fremover i vannet mer effektivt og i tillegg løfter det båten opp slik at friksjonen reduseres.

Denne masteroppgaven har i samarbeid med Flapping Foil sett på muligheten for å benytte en bøyelig hydrofoil i fremdriftssystemet i stedet for den mer tradisjonelle hydrofoilen med klaff bakerst. Oppgaven har vært todelt, det skulle bygges en prototype for denne typen hydrofoil og i tillegg skulle det lages et testoppsett for å sammenligne prototypen med den mer tradisjonelle hydrofoilen

Dessverre på grunn av en sviktende elektrisk komponent som var vital i oppsettet har det ikke blitt samlet inn noe data, men all planlegging for testingen er fullført. Testingen er derfor klar til å bli utført skulle den ødelagte delen bli erstattet av en ny. I tillegg til dette har det blitt bygget en fungerende prototype for en bøyelig hydrofoil.

Acknowledgments

Thank you to John Martin Kleven Godø and the rest of the Flapping Foil team for trusting me with the task, including me in the team and for always being helpful whether it being explaining hydrodynamics or tracking down boats for testing.

Thank you to Martin Steinert for good guidance and all the trolls of TrollLabs for their help. A special thank you to Carlo Kriesi for good help and for telling me to "stop thinking, start doing".

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Thank you to my parents for all support.

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Nomenclature

η	Propulsive efficiency
μ	Dynamic viscosity
ν	Kinematic viscosity
ω	Angular velocity
ρ	Fluid density
θ	Incoming flow angle
A	Characteristic length
c	Chord length of hydrofoil
C_P	Power coefficient
C_T	Thrust coefficient
F	Average thrust force
f	Frequency of oscillation
$h(t)$	Heave distance
L	Foil span
P	Average input power
$Q(t)$	Time varying torque
Re	Reynolds number
St	Strouhal number

T	Period of oscillation
U	Fluid velocity
$X(t)$	Time varying force in the horizontal direction
$Y(t)$	Time varying force in the vertical direction

Part I

Introduction

1 Introduction

Flapping Foil is an ongoing development project at NTNU Technology Transfer working on a new way of propulsion for boats, mainly fast ferries. The projects goal is to eliminate two problems with todays solution which is the bad efficiency of the boat propeller and the high friction force boats experience when moving through the water surface. Flapping Foil's concept solves these two challenges by utilizing an oscillation hydrofoil system that propels the boat forward and at the same time lifts it out of the water.

An important part of an oscillating hydrofoil propulsion system is of course the hydrofoil itself. Flapping Foil plans to use a foil with a rotating flap at the trailing edge, that is the rear end of the foil. However they believe that a foil with the ability to curve it's body without creating gaps or edges would be more beneficial. What is uncertain is if such a foil would perform that much better to justify the increased mechanical complexity as well as an assumed increase in cost.

2 | Defining the task

2.1 The objectives

Two objectives was given by Flapping Foil for this master thesis.

1. Build a test setup for determining the difference in propulsive efficiency between a hydrofoil with the ability to vary it's camber and one with a traditional flap.
2. Develop a concept for a variable camber hydrofoil.

These two objectives are closely relative as the second one needs to be completed for the other to be tested.

A testing rig is to be constructed with the ability to oscillate hydrofoils up and down, and vary their angle. It should also be able to measure the forces acting on the foil so that the propulsive efficiency can be calculated. In addition to this a hydrofoil prototype with the ability to curve, or vary it's camber, should be made. And to be able to compare the result of the prototypes efficiency a tradition hydrofoil with a trailing edge flap should also be made.

2.2 Technical requirements

Below follows some technical requirements that was decided upon in cooperation with the Flapping Foil team during several conversations and meetings. The terms used are described in the theory section of the thesis.

- During testing Reynolds numbers as high as between 200 000 and 300 000 should be reached.
- The Strouhal number should lie between the range 0.2 and 0.4. Testing at several different Strouhal numbers would be ideal.
- The hydrofoil should have an aspect ratio of 5. It should have the ability to change it's camber from 0 to at least 5, and the curving should occur at 60% chord.

- During testing the hydrofoil should have an angle of attack at zero, and it's heave distance should be double the chord length.

Part II

Theory

3 Oscillating foil propulsion

3.1 Hydrofoils

A short introduction to hydrofoils was given in the project thesis that can be found in appendix D. This section will elaborate more on aspects of a hydrofoil as they are described by Anderson [Anderson, 2011].

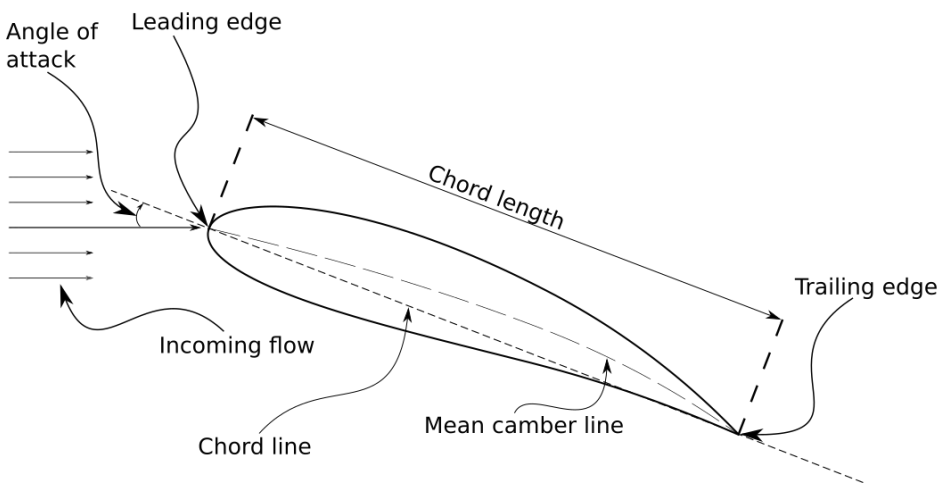


Figure 3.1: Foil terminology

3.1.1 Angle of attack

The angle of attack is the angle the chord line makes with the incoming fluid flow, it is usually denoted by the Greek letter alpha (α). Typically when the angle of attack is increased the lifting force is also increased, however by doing this the drag force also increases. Therefore it is beneficial to compromise by attempting to maximize the lift to drag force ratio. The testing done in this project will be done with zero angle of attack

which is close to the lift to drag maximum and also gives less cavitation. It should be noted that the lift to drag maximum probably lies a little higher and it would be beneficial to experiment with different angles in future testing.

3.1.2 Camber

Camber is a measurement of the foils curvature and is typically given as a percentage of the chord length. In figure 3.1 the mean camber line is drawn in, this is the middle line between the upper and lower surface. To describe foil profiles NACA numbers can be used, it is are a standard deveoloped by the National Advisory Committee for Aeronautics, the predecessor of NASA. The foil shown in the figure is a NACA5617, meaning that is ha a camber of 5% of the chord length located at the 60% chord from the leading edge. The 17 representes that the foil at its thickest has a thickness of 17% of the chord length. The same foil without camber would be NACA0017

3.2 Oscillating foil parameters

3.2.1 Strouhal Number

The Strouhal number is a dimensionless number that can be used to describe the flow produced by oscillating mechanisms [Cengel and Cimbala, 2010].

$$St = \frac{fA}{U} \tag{3.1}$$

It is based on the frequency of the oscillation (f), a caracteristic length (A) that in the case of oscillation foils is set to the wake height or double the amplitude, and the fluid velocity (U).

Earlier experiments have shown that oscillating mechanisms found in nature, that is fish swimming or bird flying, oftem have Strouhal numbers between 0.25 and 0.40 [Taylor et al., 2003]. It would seem that through evolution nature has found a common factor for efficient propulsion. Oscillating foil experiments were the strouhal number is set to be in this range have been done and it has been shown that this gives a much higher efficiency. Efficiency as high as 87% [Anderson et al., 1998] has been measured.

3.2.2 Rewriting Strouhal

As mentioned above the characteristic length in the case of oscillating foils is double the amplitude. The amplitude in this case is equal to the foils chord length c.

$$A = 2c \tag{3.2}$$

In chapter 5 we will see that a crank mechanism will be used to drive the hydrofoils heave, that is the up and down motion, and therefore it is beneficial to express the frequency f based on the angular motion ω.

$$f = \frac{\omega}{2\pi} \tag{3.3}$$

Inserting 3.2 and 3.3 into 3.1 the Strouhal number can be rewritten as is shown in 3.4.

$$St = \frac{c\omega}{\pi U} \tag{3.4}$$

As c and π are constants we see that the Strouhal number is a relationship between the angular velocity and the fluid velocity.

3.2.3 Reynolds number

Introduced by Gabriel Stokes in 1851 but named after Osborn Reynolds who popularized it in 1883, the Reynolds number is a dimensionless number that shows the ratio between inertial forces and viscous forces [Anderson, 2011]. Another way of thinking of this is as the total amount of force produced by the flow divided by the viscous forces holding the flow back. When the Reynolds number gets larger the flow reaches a point were the inertial forces gets to large for the viscous forces to hold back the flow and it becomes turbulent.

$$Re = \frac{\rho U A}{\mu} = \frac{U A}{\nu} \tag{3.5}$$

$$A = c \tag{3.6}$$

$$Re = \frac{U c}{\nu} \tag{3.7}$$

The Reynolds number is calculated from the fluid velocity (U), a caracteristic length (A) which in the case of oscillating foils is set to the cord length (c), the fluid density (ρ) and dynamic viscosity (μ) or the kinematic viscosity ($\nu = \frac{\mu}{\rho}$). The kinematic viscosity of saltwater is about $1.37 \cdot 10^{-6}$ at 10°C [engineeringtoolbox, 2017], for higher accuracy this should be measured during experiments.

3.2.4 Hydrofoil trajectory

The heaving motion of the hydrofoils is produced by the crank mechanism of the rig, and the hydrofoils heave is therefore Dependant on the angular velocity ω. The crank arms length is equal to the foils chord length c which sets the amplitude of the heave. This makes the heave distance equal to $2c$. The hydrofoils vertical position can be calculated using equation 3.8. If we take the derivative of equation 3.8 with respect to time we get the velocity of the heave, this is shown in equation 3.9.

$$h(t) = c \cdot \sin(\omega t) \tag{3.8}$$

$$\dot{h}(t) = c\omega \cdot \cos(\omega t) \tag{3.9}$$

As mentioned in 3.1.1 the foils should have zero angle of attack relative to the incoming water flow. To measure precisely the water flow would be near impossible but a good approximation is to assume that the water does not move and calculate the flow trajectory based on the horizontal boat velocity and the vertical heave velocity.

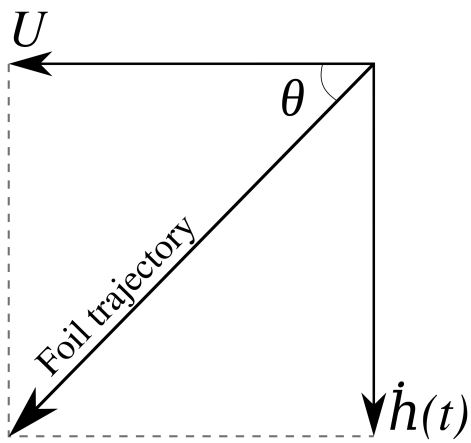


Figure 3.2: The foils trajectory can be found using U and $\dot{h}(t)$.

By using simple trigonometry one can calculate the angle of the flow which with zero angle of attack is also the foil angle. This is shown in equation 3.10.

$$\tan(\theta) = \frac{\dot{h}(t)}{U} = \frac{c\omega}{U}\cos(\omega t) \tag{3.10}$$

3.2.5 Forces and efficiency

As the foil oscillates in water it is subjected to time varying forces in the horizontal x-direction and the vertical y-direction. These are denoted $X(t)$ and $Y(t)$ respectively. In addition there is a torque $Q(t)$.

From this we can define the average thrust force F, and the average input power P [Cengel and Cimbala, 2010].

$$F = \frac{1}{T}\int_0^T X(t)dt \tag{3.11}$$

$$P = \frac{1}{T}\int_0^T (Y(t)\dot{h}(t) + Q(t)\dot{\theta}(t))dt \tag{3.12}$$

The foil will be secured in the 25% chord position which is known as the assumed aerodynamic center. The aerodynamic centre is the point where the torque is constant at all angles of attack. In this case it is assumed that the center of pressure, that is the point where the forces act through and therefore where the torque sums up to zero, lies close to the aerodynamic center. Because of this the second term in equation 3.12 cancels out.

$$P = \frac{1}{T}\int_0^T Y(t)\dot{h}(t)dt \tag{3.13}$$

It should be noted that neglecting $Q(t)$ is not accurate and it is possible that this will lead to higher efficiency readings. But as the purpose of testing is to compare the different hydrofoils to each other this will not affect the results much.

Both the thrust force and the input power can be expressed as dimensionless coefficients [Cengel and Cimbala, 2010], and the efficiency is defined as the ratio of these two.

$$C_T = \frac{F}{\frac{1}{2}\rho c L U^2} \tag{3.14}$$

$$C_P = \frac{P}{\frac{1}{2}\rho c L U^3} \tag{3.15}$$

$$\eta = \frac{C_T}{C_P} = \frac{FU}{P} \tag{3.16}$$

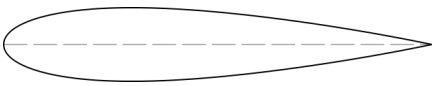
Part III

Development

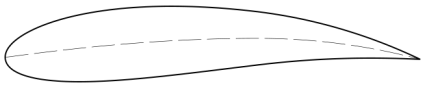
4 | Hydrofoils

The two hydrofoils were both based on the same foil profile, the NACA5617. This meaning that the curving foil would vary between the NACA5617 and the NACA0017, and the the flap foil is a NACA5617 with a joint added at the 20% chord line from the trailing edge. Both foils should have similar attachments in the 25% chord lines as they are made to be used in the same testing rig. This meant a 20mm axle for tilting, and a 10mm axle going through the center of the 20mm axle for controlling either the curving or the flap.

The NACA5617 profile was chosen based on the requirements mentioned in chapter 2, and created by the help of an airfoil generator [Airfoiltools, 2017].



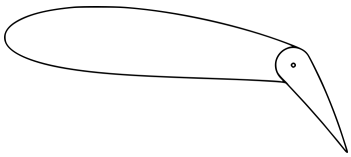
(a) NACA0017



(b) NACA5617

Figure 4.1: Curving hydrofoil

(a) Negative flap angle



(b) Positive flap angle

Figure 4.2: Hydrofoil with flap

4.1 Curving hydrofoil

The foil should be able to curve, or vary it's camber, without having any gaps or abrupt edges that one usually would find on a foil with a trailing edge flap. To achieve this a continuous hull being moved by an internal mechanism became part of the concept early on.

4.1.1 First prototype: The basic idea

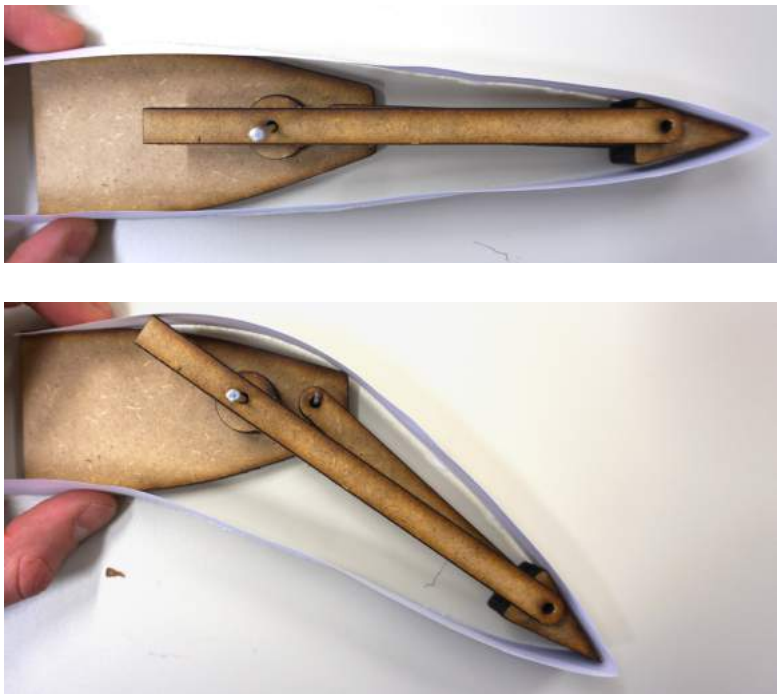


Figure 4.3: Early rough prototype.

Figure 4.3 shows an early rough prototype. It was made by laser cutting MDF parts and attaching them with glue and using nails as joints. A strip of paper is used as the hull.

This prototypes main purpose was to start the development process and getting something physical to work with, starting to build is an effective way of getting to understand an idea. It shows the main idea of a mechanism moving and by making this it became clear that a stiffer hull or more underlying support should be added to withstand the water pressure and allow the hull to form better.

4.1.2 Second prototype: The gripper

The fin grippers by Festo [Festo, 2017] are, as the name indicates, originally made for robot grippers. The concept being that they will bend and take the shape of the object that the robot arm is lifting. The next foil prototype tried to borrow from this design to make a trailing edge that would push back against the water pressure.

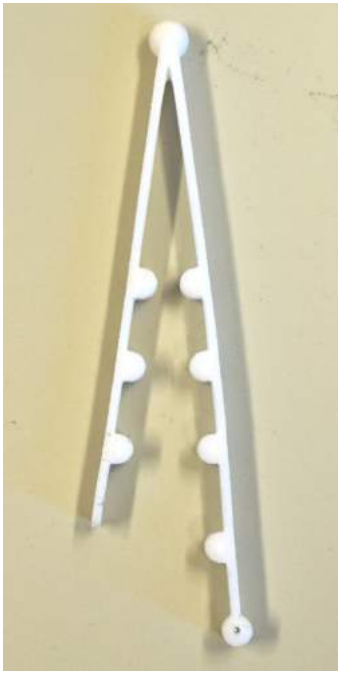


Figure 4.4: Fin gripper.

Figure 4.5: Side force.

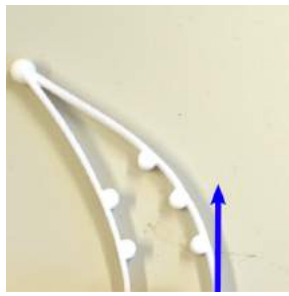


Figure 4.6: Pushing leg to curve.

Figure 4.4 shows a single fin, printed using the Blueprinter 3D printer. Festo uses several of these to form a gripper. Figure 4.5 shows how when a force is applied the fin curves towards the force, and figure 4.6 shows that it is also possible to control the fins curving by pushing on its legs. Not shown in the figures are the stiff bars that attach the side walls to each other, going between the circles attached to the walls. These bars stiffens up the structure and makes it more resistant to pressure from the outside.

In figure 4.7 we see the foil based on the gripper. It is also printed using the Blueprinter and has push rods attached to each side wall of the trailing edge that can move independently of the foils main body.

Even though the surface is continuous this foil still moves its trailing edge much like a foil with a flap. Also it seems difficult to manipulate the foils geometry by moving the hull directly. It seems that it would be more beneficial to have an underlying structure for the hull to glide on top of.

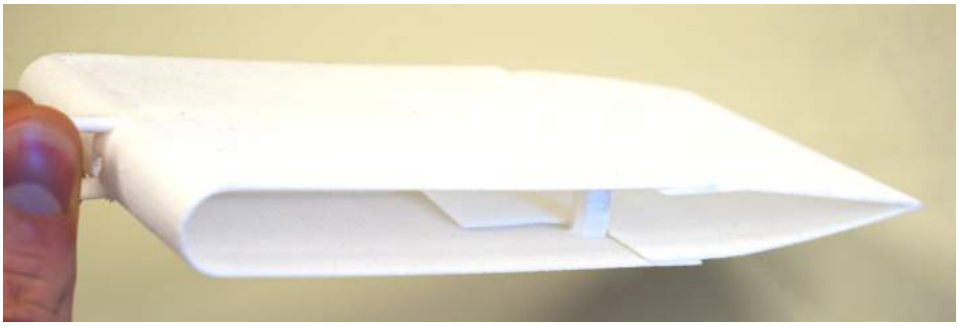


Figure 4.7: Hydrofoil prototype based on fin gripper.

Figure 4.8: text

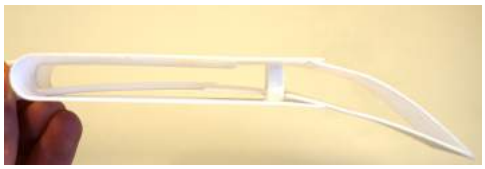


Figure 4.9: text

4.1.3 Third prototype: The sail

Inspired by a patent for mechanically operated sails on sailboats [Morris, 1967] the next prototype was an attempt to give the hull a more rounded underlying surface to rest on. It was assumed that the water pressure would push the hull to form around these surfaces.

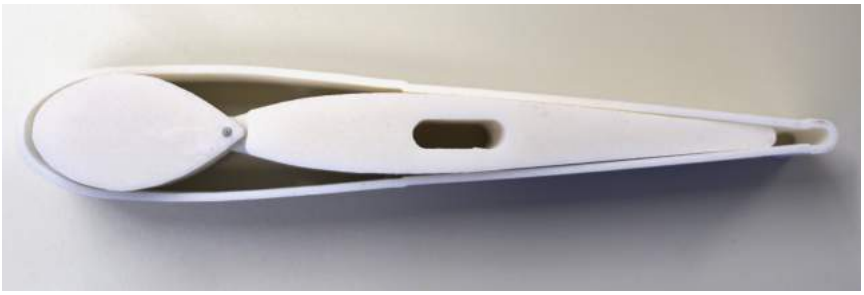


Figure 4.10: Patent inspired.

(a) **(b)**

Figure 4.11: The hull needs to be attached.

Made using the Blueprinter the foil had a hinged body with a loose hull that slides freely. It was imagined that the foil would attach to the boat in the center of the front body and rest on a rod going through the slot in the rear body. The front part could then be rotated and the rear parts attachment would make the foil curve. The hull turned out to be too stiff and in addition it was clear that it needed some form of attachment to the body for it to curve better. Figure 4.11 shows how the hull needed to be pressed together to stay close to the body.

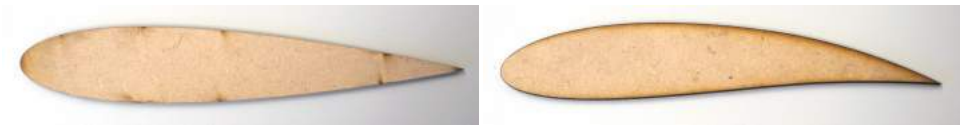
(a) **(b)**

Figure 4.12: Updated prototype with attached hull.

The prototype was reprinted but this time with the hull attached to the rear body. This alteration made the foil curve much better, this is shown in figure 4.12, but the hull still had some trouble. The original sail patent had a more complex mechanism that formed a better underlying surface, in addition the hull seems to be to long when bending and a way to adjust the length of the hulls sidewalls should be added.

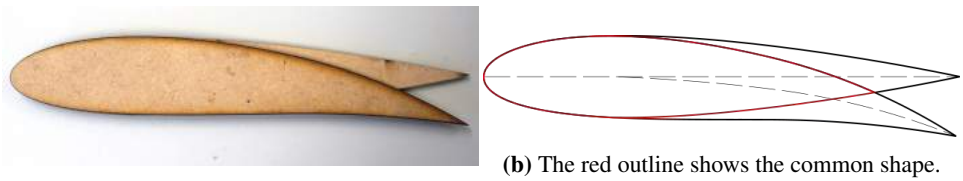
4.1.4 Fourth prototype: The mash-up

The two foil profiles, NACA5617 and NACA0017, was cut out using the laser cutter to get a more hands on way of working with the shapes. It was discovered that when stacking them on top of each other the front parts of the profiles are quite similar, this is shown in figure 4.14a. Figure 4.14b shows how after discovering this the profiles was divided into three shapes. The common shape between the two that is outlines in red, and the two extra "tails" that are left after splitting up.



(a) NACA0017 **(b)** NACA5617

Figure 4.13: NACA0017 and NACA5617 cut out using laser cutter.



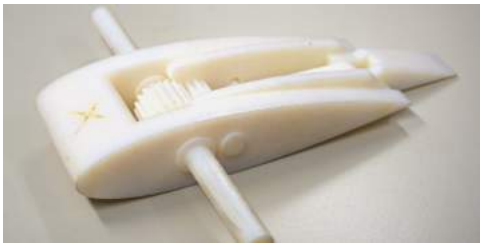
(a) Laser cut profiles stacked

(b) The red outline shows the common shape.

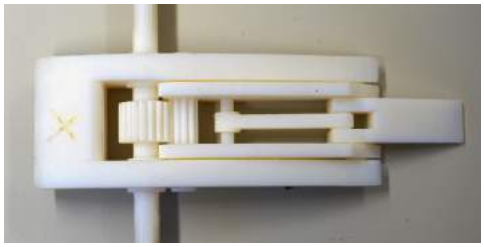
Figure 4.14: The two foil profiles stacked on top of each other.

This common area between the two profiles was made into the base part of the foil, and the two so called "tails" was combined into one lever arm that was attached to the base. The end of the lever arm was attached on a joint to allow some extra rotation. The result is shown in figure 4.15, it is 3D printed using the Objet Alaris 30 printer. The mechanism is operated by turning the axle which is connected to the lever arm by gears.

Looking at the outline of this foil in figure 4.15c and 4.15d one can see that the curving is much better than on previous prototypes, and it gives a much better surface for a hull to form around.



(a) The prototype.



(b) Top view.

(c) NACA0017.

(d) NACA5617.

Figure 4.15: First printed prototype.

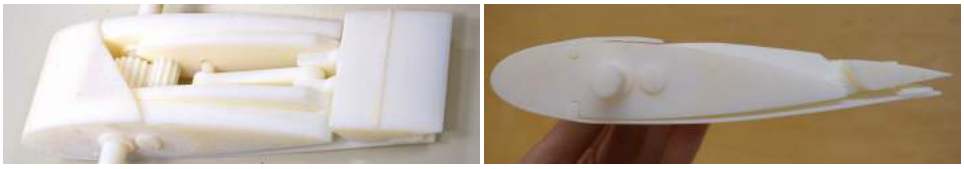
To see if the hull also could be printed using the Objet three square samples were printed of 0.3, 0.4, and 0.5mm thickness. The flexibility and strength of these samples was far better than expected, figure 4.16 shows the sample with 0.5mm thickness. It was later during building of the final prototype discovered an error with these sample tests. The samples was printed laying flat on the printer bed while the hulls because of their shape was printed standing up. This orientation of the hulls gave far less strength than the samples had indicated.

Figure 4.16: Flexibility test.

The hull was modeled after the NACA0017 but with the rear part opened up so that they could slide independently of each other and accommodate for the length differences during curving. Notches was added as a way of securing the hull to the upper and lower sides of the hull at about the 20% chord line. On the trailing edge grooves were added so that the hull could be attached and slide freely.

Figure 4.17 shows the remade prototype with the hull. The hull broke during assembly

and because of this the wall thickness of the hull was changed from 0.5mm to 1.5mm. The trailing edge also had to be altered as the attachment for the hull was far to weak. In addition to this the hull was extended so that sidewalls could be added to the foil. Figure 4.18 shows the prototype with these alterations done.

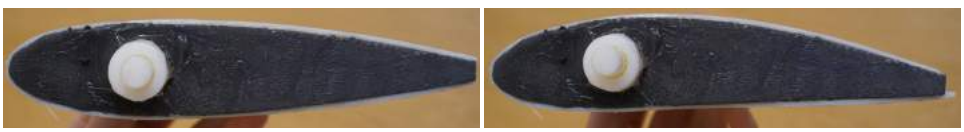


(a) **(b)**

Figure 4.17: The first hull broke.

(a) Sidewalls. **(b)** Attachment for hull on trailing edge.

Figure 4.18: Hydrofoil with sidewalls.



(a) NACA0017 **(b)** NACA5617

Figure 4.19: Hydrofoil with sidewalls curving.

With the new hull and attachments the foil curved nicely and this was considered as the first prototype to work properly. However there were still some areas that could be improved before moving on to building the larger hydrofoil. It took quite an amount of force to turn the axle making the foil curve, two factors were linked to this. The first being that some force was needed to bend the sidewalls, and the second the gearing between the axle and the lever arm. The sidewalls was removed because of this as it was assumed that it would not affect the final hydrofoil much. The two gears were swapped changing the gear ratio

to a reduction, this made the axle easier to turn and also gave it more travel distance which made it easier to be more accurate in deciding how much to curve the foil.

Figure 4.20 shows the final version of these smaller prototypes. The large prototype was built based on this foil.

Figure 4.20: Final version.

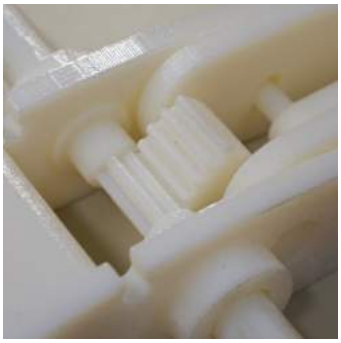
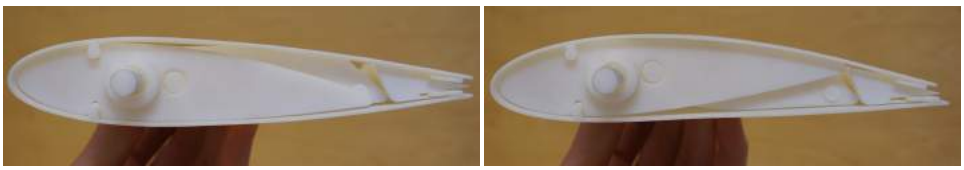
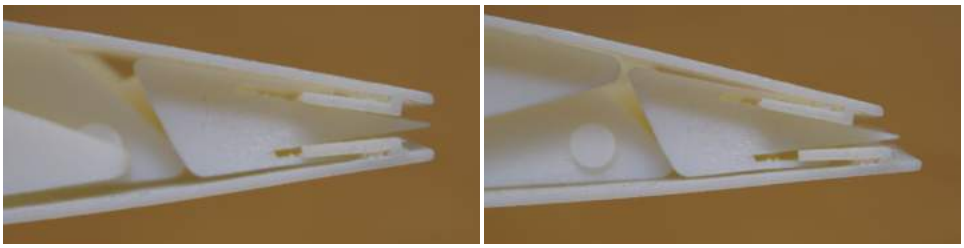


Figure 4.21: Gears were changed on the final version.



(a) NACA0017 **(b)** NACA5617

Figure 4.22: Final version curving.



(a) **(b)**

Figure 4.23: Hull attachment on trailing edge allows the hull to slide.

4.1.5 Final prototype

To build the final large prototype the small prototype from the last section was extended. For the hydrofoil to have an aspect ratio of five the foil needed to have a span of 90cm, this is far larger than the Objet can print and the foil was therefore divided into five sections. Three middle sections and two side sections with attachments for the test rig.

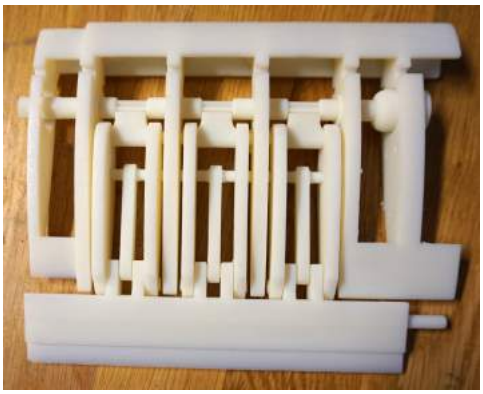


Figure 4.24: One of the three middle sections.

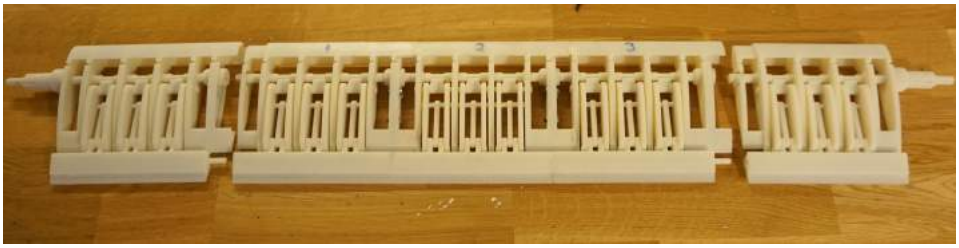


Figure 4.25: Middle sections glued together with sides ready to be attached.

The sections were attached to each other using both screws and epoxy glue. They were made with an overlap to give a larger area for gluing, and the axles go together with square male and female connectors.

The hull was also extended and printed in eight parts that slid on to the foil and overlapped each others edges. The hulls right before being removed from the printer can be seen in figure 4.26, as mentioned in section 4.1.4 this printing orientation gave weaker walls. Because of this many of the thinner overlay edges had pieces breaking off during cleaning and assembly. However the finished hull, while not being a promising contestant in a beauty contest, forms a complete surface on the wing and in that way does the job it is supposed to do. Should a new hydrofoil be made in the future it would be wise to use something else for the hull, for example a thin but sturdy thermoplastic sheet could be

heated and formed around the inner structure forming the same shape as the one already made but with a single large hull that is much stronger.

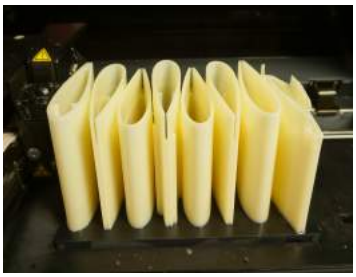


Figure 4.26: Printed hull sections.

Figure 4.27: Axle connectors.

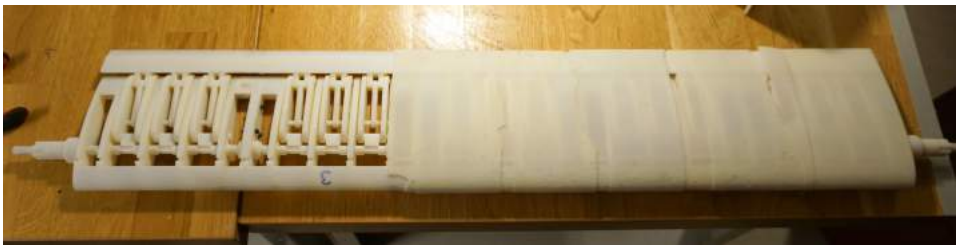


Figure 4.28: Hull being assembled.

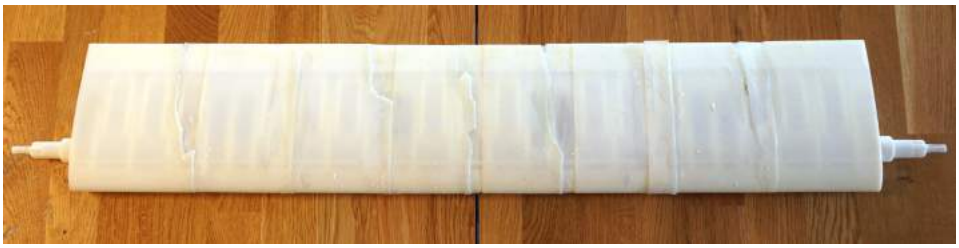


Figure 4.29: Finished variable camber hydrofoil.

4.2 Hydrofoil with flap

Because the two hydrofoils are to be used in an experiment on the difference in hydrofoils that curve and those with a trailing edge flap, the other aspects of the foils should be as similar as possible so that they do not interfere with the results. Therefore the flap hydrofoil was also made using the Objet 3D printer so that they would have similar surface qualities.

4.2.1 First prototype: The chain

A much bigger challenge on this foil, compared to the other, was transferring the rotational motion from the axle going through the 25% chord line to the flap in the back of the foil as the dimensions are quite small. The first attempt at this was with a chain and sprocket design.

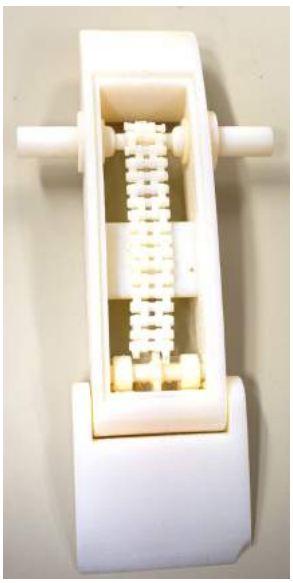


Figure 4.30: Chain drive on flap.

Figure 4.31: Broken chain.

Unfortunately because of the small dimensions the chain was not strong enough and broke during the removal of the support material before any testing on the prototype could be done. Because of this it was decided that the chain design was not strong enough to endure the water pressure during the experiment that would come later and the design was abandoned.

4.2.2 Second prototype: The four-bar linkage

The chain and sprocket design from the last section can be viewed as a bit redundant as the sprockets do not need to do full rotations. Instead the chain was replaced with bars forming a four-bar linkage. This works similar to the chain but is much stronger because it uses solid bars instead.

The first version of this prototype transfered the motion from the four-bar with two gears, thereby reversing the four-bars motion. During oscillation the flap will always be pointing along the horizontal line, by adding an extra gear one can hold the axle stationary during the foils pitching motion and the flaps angle relative to the boat will be constant.

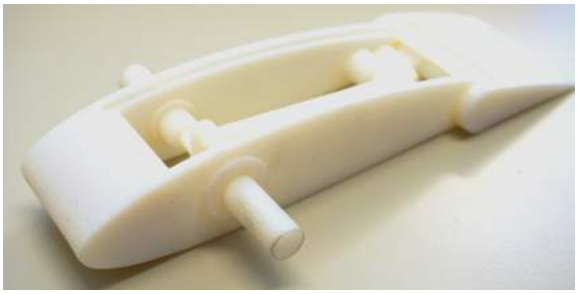
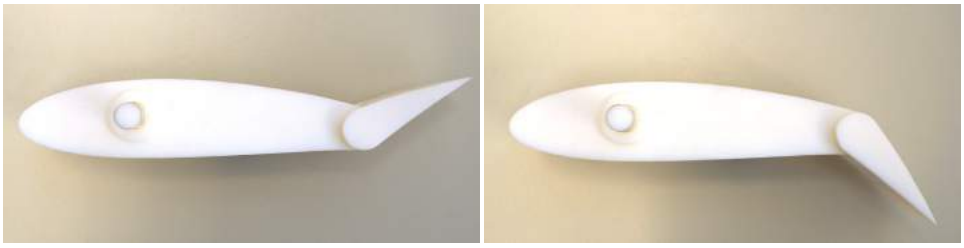


Figure 4.32: Hydrofoil with trailing edge flap.

Figure 4.33: Three gears connect the four-bar to the flap.



(a) **(b)**

Figure 4.34: Negative and positive flap angle.

4.2.3 Final prototype

Similar to the final large prototype of the curving foil, this hydrofoils was also Printed in five sections. The design for attaching the sections to each other was very similar to the previous one with screws and epoxy glue, and the same type of connectors for the axle. However despite being made in the same way this hydrofoil required sanding with a Dremel for the parts to fit together, and in addition what turned out to be a very unfortunate turn of events the gears were fused together without possibility for seperating them. This will be discussed further in chapter 6.

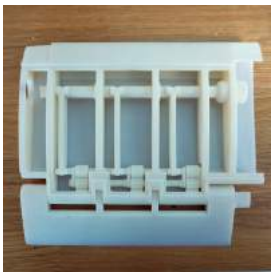


Figure 4.35: Middle section.

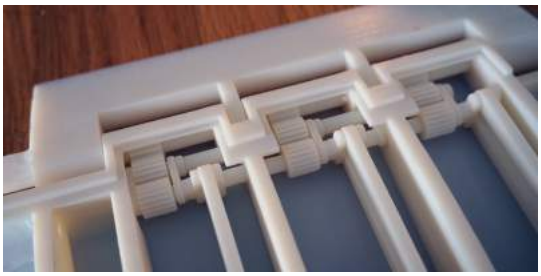


Figure 4.36: The gears were stuck.

Figure 4.37: The finished hydrofoil with a trailing edge flap.

5 | The test rig

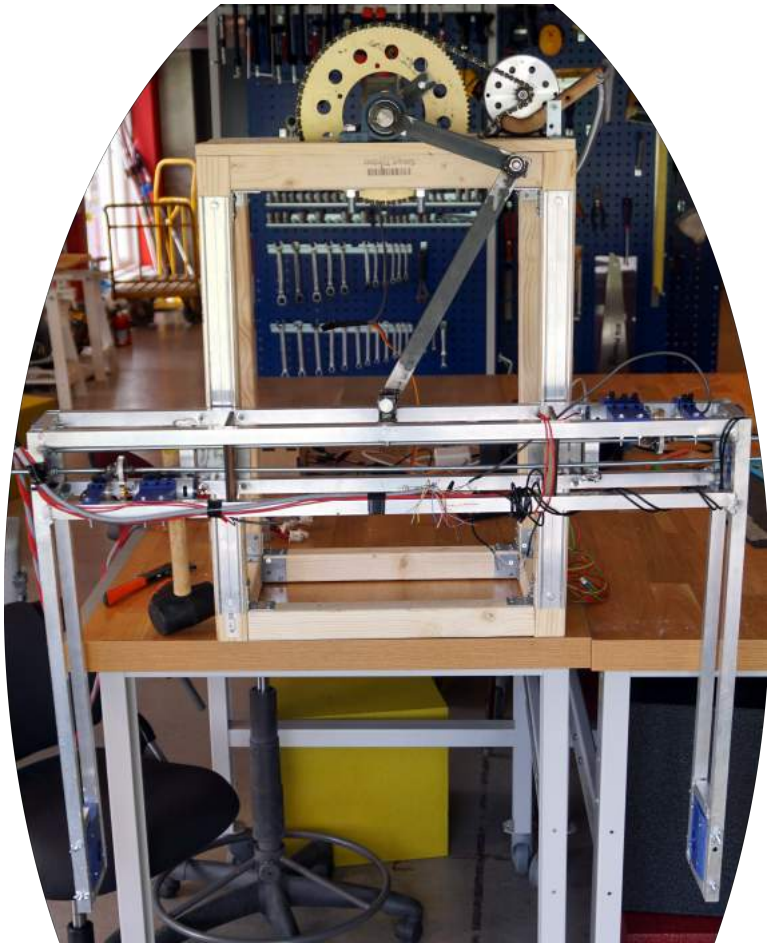


Figure 5.1: The testing rig

5.1 Structure

The rig can be divided into two parts, the base frame and the foil frame. The foil frame was made out of 20x20mm aluminum square pipes with 2mm wall thickness and 3D printed parts to hold bearings and electronics. It attaches to two linear bearings on the base frame. A motor driven crank mechanism sitting on top of the base frame drives the foil frame, and therefore the hydrofoil, up and down. The base frame was built using 2x2 inch lumber.

5.2 Electronics and actuation

All electronics are illustrated in appendix A.

5.2.1 Arduino

Arduino is the name of the open source hardware and software project that make microcontroller boards that goes under the same name. These boards can be used for a variety of projects both by hobbyists and professionals. [Arduino, 2017]

All the electronics in this experiment is being controlled by an Arduino Mega ADK, and the code is written using the Arduino IDE.

The Arduino programming language is a "dialect" of the programming language C++. This meaning that it is a simplified version of C++. While programming one can include in the code so called "libraries" that are collections of functions that can be used.

Figure 5.2: Arduino Mega ADK

5.2.2 Heave

To drive the hydrofoils up and down vertically a simple crank mechanism was used. It consists of a crank arm mounted on an axle, the axle was driven by an 800W 36V DC motor connected to the axle with a chain and sprockets.

To measure the axles angular velocity (ω) a rotary encoder is connected to it. Rotary encoders are electro-mechanical devices that measure angular position, in this case they divide one rotation into 800 steps. They can count in both negative and positive directions. By measuring how many steps is registered over a time interval the velocity can be calculated.

Figure 5.3: Crank mechanism.

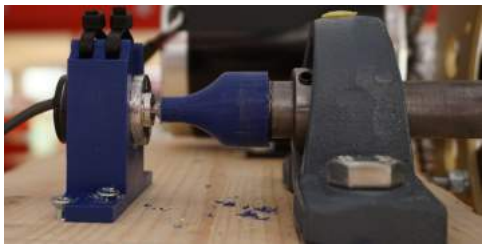


Figure 5.4: Rotary encoder for measuring angular velocity.

5.2.3 Pitch and flap

To control the Hydrofoils pitch, or angle, as well as the flap and curving 12V DC motors was used, they were connected to the Arduino through a H-bridge. Also here rotary encoders were connected to the motors, in this case to measure angular position. The motors drive axles that are connected to the hydrofoils axles by push arms.

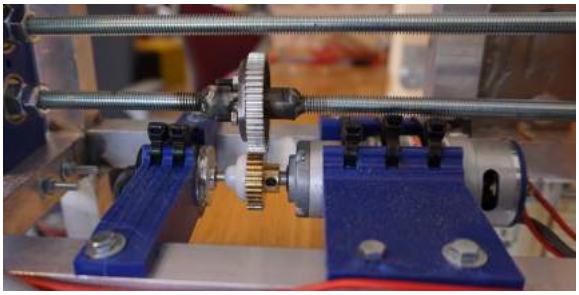


Figure 5.5: Motor turning axle with rotary encoder connected.

5.2.4 GPS velocity

To measure the speed of the boat (U) a GPS module was attached to the Arduino. The GPS uses 3.3V digital signals while the Arduino operates with 5V, the signals between the two therefore needed to be converted. The Arduino library "TinyGPS++" [Hart, 2017] was used to process the data from the module.

Figure 5.6: GPS module.

A simple test of the speed accuracy was performed by driving in a car with the GPS set up and comparing its readings with the cars speedometer and a GPS speed app for smartphones [speedview, 2017]. The GPS readings were very close to those of both the car and the APP, however it must be stated that this test was very unscientific and comparison was done only by visually observing. Therefore the GPS should be viewed as a source of error.

5.2.5 Load cells

Figure 5.7: Load Cell.

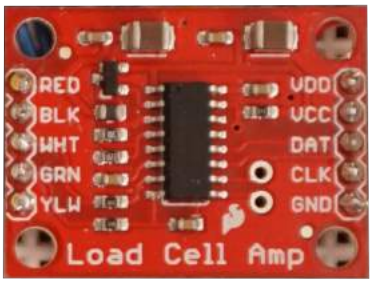


Figure 5.8: Load Cell amplifier.

The load cells are button compression cells with a capacity of 200kg. They are mounted around one of the bearings with measuring axis perpendicular to each other, as can be seen in figure 5.9. This allows the measuring of forces in both X and Y direction.

Figure 5.9 also show how the load cells are pushed against the bearing by tightening the bolts against them. The cells only measure forces in one direction therefor by preloading them the setup can measure both positive and negative forces.

The load cells connect to amplifiers, that can be seen in figure 5.8. The amplifiers convert the signals from the cells to a output that the Arduino can understand. In the code this input is managed by the library "HX711" [HX711, 2017]

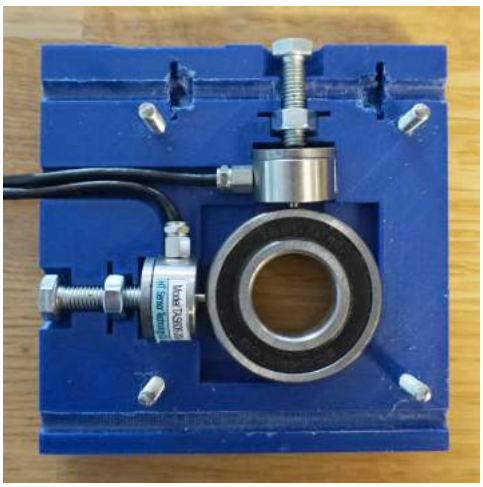


Figure 5.9: Load Cells and bearing.

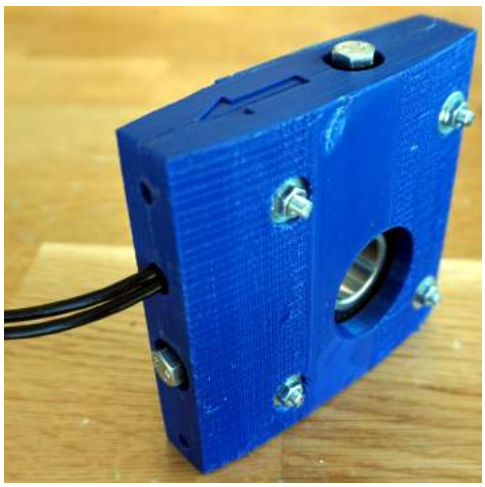


Figure 5.10: Assembled bearing housing.

5.2.6 SD card unit

During the experiment data will be logged onto SD cards by using a SC card unit connected to the Arduino.

The data that will be logged is the horizontal speed (U), the angular speed of the crank (ω), the forces in the horizontal direction (X), the forces in the vertical direction (Y), and the time (t).

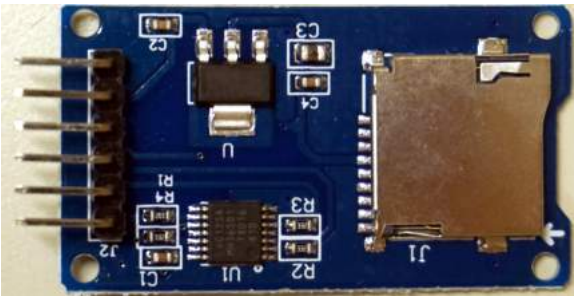


Figure 5.11: SD card unit

5.2.7 The Arduino code

The entire Arduino code can be fount in appendix B. Every part of the code has been tested separately and works, but because of the broken motor controller not enough testing of the code as a whole was done.

The entire code can be broken down into four actions that occur once every second.

1. It retrieves the horizontal velocity, U.
2. Based on U and the Strouhal number it sets the angular velocity, ω.
3. The foil angels are updatet based on U, ω, and the time t.
4. All these values as well as the force readings X and Y are written to the SD card.

6 Unforeseen events

6.1 Gears

Because of what seems to be a calibration problem with the Objet printer the gears on the final hydrofoil with a trailing edge flap was stuck. A day was spent trying to get them working but without success, and it was decided that severe rebuilding was needed to get them to work something the time schedule did not allow. It was therefore decided that the project would keep going without the possibility to adjust the flap angle. Instead the testing would be done with the stationary flap and an estimate of best and worst gain in efficiency. Even though not ideal this would give a indication of the curving foils efficiency compared to that of a foil with a trailing edge flap.

6.2 Motor controller

The motor controller controlling the heave motor stopped working and instead of varying the motor speed drove the motor at full speed at all time. After examining the controller it did not seem to be something easily resolved and it was therefore attempted to build a new controller. This controller would be constructed using MOSFET transistors.

The transistor needed to be rated for more than 36 volts as that is the motor operating voltage, also the motor being 800 watts the current would be at about 23 amps but with amp peaks reaching 30 amps at motor start and stop. Normally one would use several transistor connected in parallel to divide up the current but unfortunately there were no transistors with high enough current ratings. This left ordering new parts as the only option but unfortunately this occurred to close to the thesis deadline for the parts to arrive in time. Sadly this stopped all plans of testing.

Part IV

Testing

7 Hydrofoil testing

Because of the events described in section 6.2 this section is quite different from what was initially planned. Therefore instead of describing testing that have been done and looking at data, this part will focus on how the testing would have been done and also how the data would have been processed. It is the authors hope that this could be of help if someone where to pick up the project later.

7.1 Temperature

First the temperature of the water is measured as the kinematic viscosity is temperature dependent and will be used later together with the horizontal speed measurements to calculate the Reynolds numbers.

7.2 Lift-to-drag ratio

A typical measurement of performance for all foils is the relationship between lift and drag forces C_L/C_D, this is measured by driving the foils in water without oscillating. As the two hydrofoil prototypes are based of the same foil profile they should have similar lift-to-drag ratios, however because the variable camber foil has a continuous surface it will likely be higher.

The measurements are done at different speeds so that the ratio can be compared to the changing Reynolds number.

7.3 Efficiency measurements

To determine the propulsive efficiency of the oscillating hydrofoils they are driven at varying velocities while logging the forces acting on one of the support bearings. This is done three times for each hydrofoil with different Strouhal numbers. The Strouhal numbers being 0.2, 0.3, and 0.4.

7.4 Data processing

During the testing the horizontal speed U, the angular speed of the crank ω, the forces in the horizontal and vertical directions X and Y, and the time t was logged once every second. This data can be processed using the computing software Matlab.

All data should first be sorted from lowest to highest value of U, this is so that it can be plotted with an ascending Reynolds number. The force measurements are given in pounds and should therefore be converted to Newtons, and the time from milliseconds to seconds.

Thrust force, input power and efficiency can then be calculated as described in section 3.2.5 by using the numerical integration function "cumtrapz" in Matlab.

Finally the results for efficiency at each value of the Strouhal number can be plotted against the Reynolds numbers.

8 Uncertainty in the testing

8.1 GPS

The accuracy of velocity measured by a GPS can be varying. Generally they are fairly accurate over longer distances of constant speed but may be less accurate if the speed is varied a lot. Because of this it is reasonable to question the accuracy of U and therefore the Reynolds number. A safer alternative to the GPS could be a pitot tube which uses pressure measurements to decide the velocity.

8.2 Computational power

The hydrofoil angle is calculated once every second, it is uncertain if this is to fast for the Arduino to keep up with its calculations. To control this the code could be altered to also log the angle. Should this be an issue one could try to increase the time between the Arduino's calculations, or abandon the Arduino for something with more computational power like for example a Raspberry Pi.

8.3 Surface properties

Because of the different orientations during the 3D printing the two hydrofoils have a different feel to their surfaces. It is therefore possible that they have different surface qualities which would, to some degree, affect the results. Treating the surfaces in some way could resolve this, for example by painting them.

8.4 Torque

In section 3.2.5 torque was neglected as it is assumed to be very small because of the hydrofoils attachment to the rig. This could be a huge error should this assumption be wrong. To resolve this rebuilding the rig is necessary, the least comprehensive way would be to attach force sensors of some kind to the push arms controlling the hydrofoils angle.

Part V

Discussion and conclusion

9 | Variable camber hydrofoil

A hydrofoil meant for propulsive oscillation with the ability to vary its camber has been developed as a part of this thesis, the process was describes in chapter 4. Unfortunately because of a failing motor controller the foil has not been tested therefore it remains to see how well it performs. However the foils mechanism works well and it is assumed that because of it's continuous surface and ability to bend without making abrupt edges it would outperform a hydrofoil utilizing the traditional trailings edge flap.

The design could with some alterations be used in the construction of hydrofoils on actual real size boats. The most important alteration being the trailings edge which is possibly the weakest part of the design, the attachment is not very strong and it is possible that friction will be an issue in the way the hull is attaches.

10 Test rig for oscillating hydrofoils

Because of the failing motor controller it is difficult to say how the test rig would have performed, however a working concept for a test rig has been developed.

The biggest flaw with the test rig is its inability to measure torque as during the development process this was assumed to not be of importance. This limits the rigs ability to be used for other hydrofoil experiments, however it is possible to adapt it for this purpose should this be desired.

11 | Further work

First and foremost the motor controller should be replaced so that the testing can be performed, results are needed so that a decision can be made on whether the concept is something worth developing. Should that be the case it is possible that it would be beneficial with a more aggressive curving foil and one could look into altering the design to achieve this.

The test described in this thesis operates with an angle of attack at zero, future testing should experiment with different values. Choosing the angle of attack is all about trying to find the most beneficial relationship between lift and drag forces, and while this typically lies near zero it is not necessarily the case.

Further development of a prototype for actual use on boats should be done, the biggest challenge would probably be to find a suitable solution for the hull. It is assumed that aluminum sheets could be used.

A less technical suggestion for future work would be to perform a cost analysis comparing the new hydrofoil to a traditional one.

12 | Conclusion

The objective of this master thesis was to build a test setup so that it could be decided whether or not applying a variable camber hydrofoil instead of a traditional foil with trailing edge flap would be beneficial enough to justify the increased mechanical complexity as well as the assumed increased cost. In addition to this the thesis also sought out to develop a concept for a variable camber hydrofoil.

The question concerning the difference in efficiency has unfortunately not been answered because of a failure in test rig hardware but all planning has been done so that everything is ready should the broken part be replaced. Therefore, even though no data has been collected, the development of a test setup has been a success.

A prototype for a variable camber hydrofoil has been built and proves that the mechanical aspects of it is possible. More testing needs to be done, but the prototype is a good basis for further development. Not just for test usage but also for real size propulsion systems.

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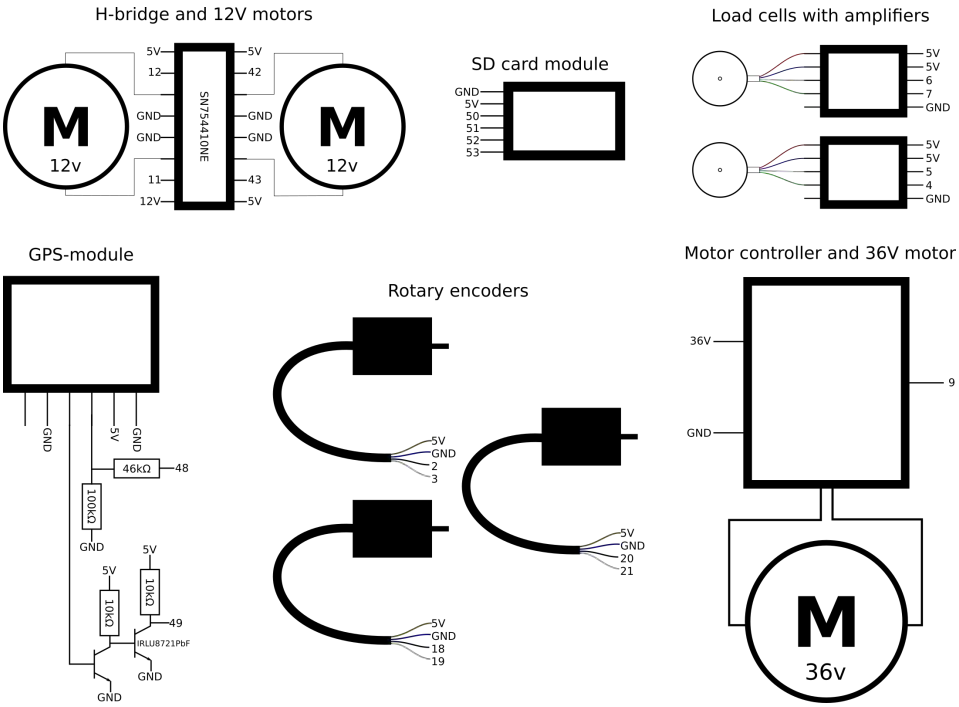
Appendix

A | Electronics

Overview of all electronics except the Arduino board. Numbered connections refer to ports on the Arduino.



B | Arduino code

```
#include <math.h>
#include <Encoder.h>
#include "HX711.h"
#include <TinyGPS++.h>
#include <SoftwareSerial.h>
#include <SD.h>
#include <SPI.h>

//////////////////////////// Rotary encoders
Encoder pitchEnc(18, 19);
Encoder flapEnc(2, 3);
Encoder motorEnc(20, 21);

const double St = 0.3; //Strouhal number (0.2, 0.3 and 0.4)

const double c = 0.18; // chord length

double t = 0.0;
double currentMillis;
double previousMillis;

double omega;
int previousRead = 0;
double previousOmegaTime =  0;
double StOmega;
int omegaPin = 9;
int omegaValue = 50;

double angle = 0.0;
double measuredAngle = 0.0;
int encSens = 1;

double rpc = 0.007853981634; // radians per rotary click
```

```
//////////////////////////////////// pitch and flap motors
int motorPitch[] = {12, 11};
int motorFlap[] = {42, 43};
int motorSpeed = 255;

//////////////////////////////////// Load cells
#define calibration_factor -7050.0
#define DOUT1  6
#define CLK1  7
#define DOUT2  5
#define CLK2  4
HX711 Xforce(DOUT1, CLK1);
HX711 Yforce(DOUT2, CLK2);

//////////////////////////////////////////////// GPS
static const int RXPin = 49, TXPin = 48;
static const int GPSBaud = 4800;
TinyGPSPlus gps;
SoftwareSerial ss(RXPin, TXPin);
double StartSpeed = 1;
double U = StartSpeed;
//////////////////////////////////////////////// SD

File SDcard;
int pinCS = 53;

//////////////////////////////////////////////////////////// Setup
void setup() {

        Serial.begin(9600);
        ss.begin(GPSBaud);

        //////////////////////////////////// pitch and flap motors
        int i;
        for(i = 0; i < 2; i++){
        pinMode(motorPitch[i], OUTPUT);
        pinMode(motorFlap[i], OUTPUT);
        }
        //////////////////////////////////// Load cells

        Yforce.set_scale(calibration_factor);
        Yforce.tare();
        Xforce.set_scale(calibration_factor);
        Xforce.tare();
```

```
        pinMode(pinCS, OUTPUT);
}
//////////////////////////////////////////////////////////////////// LOOP
void loop() {

        currentMillis = millis();

        t=millis();


        if( currentMillis-previousMillis > 1000 ){

                getU();         // get U from GPS

                setOmega();     // Set omega based on U and Strouhal

                pitchDrive();   // Update foil angle

                SDwrite();      // write to SD

                previousMillis = currentMillis;
        }
}
//////////////////////////////////////////////////////////////////////

void pitchDrive(){

        //angle in radians
        angle = 1.5*atan( (c*omega*cos(omega*t*PI/500)) / U );

        //800 klick per 2pi radians
        measuredAngle = pitchEnc.read()*PI/400;

        if(angle - measuredAngle > encSens){
                pitchNeg(255);
        }

        else if(angle - measuredAngle < encSens){
                pitchPos(255);
        }
        else{
                pitchStop();
        }
```

```
}
void pitchPosition(int setAngle, int rotSpeed){

        while(abs(setAngle - pitchEnc.read()) > 2){

                if(setAngle > pitchEnc.read()){

                if(setAngle - pitchEnc.read() > 10){
                        motorSpeed = rotSpeed;
                }
                else{
                        motorSpeed = 60;
                }
                pitchPos(motorSpeed);
                }
                if(setAngle < pitchEnc.read()){

                        if(setAngle - pitchEnc.read() < 10){
                                motorSpeed = rotSpeed;
                        }
                        else{
                                motorSpeed = 60;
                        }
                pitchNeg(motorSpeed);
                }
        }
        pitchStop();
}
void flapDrive(){

        //angle in radians
        angle = 1.5*atan( (c*omega*cos(omega*t*2*PI)) / U );

        measuredAngle = flapEnc.read()*PI/400;

        if(angle - measuredAngle > encSens){
                flapPos(255);
        }

        else if(angle - measuredAngle < encSens){
                flapNeg(255);
        }
        else{
                flapStop();
        }
```

```
}
void flapPosition(int setAngle, int rotSpeed){

        while(abs(setAngle - flapEnc.read()) > 2){

                if(setAngle > flapEnc.read()){

                        if(setAngle - flapEnc.read() > 10){
                                motorSpeed = rotSpeed;
                        }
                        else{
                                motorSpeed = 60;
                        }
                        flapPos(motorSpeed);
                }
                if(setAngle < flapEnc.read()){

                        if(setAngle - flapEnc.read() < 10){
                                motorSpeed = rotSpeed;
                        }
                        else{
                                motorSpeed = 60;
                        }
                        flapNeg(motorSpeed);
                }
        }
        flapStop();
}
void pitchNeg(int motorSpeed){
        analogWrite(motorPitch[0], 0);
        analogWrite(motorPitch[1], motorSpeed);
}
void pitchPos(int motorSpeed){
        analogWrite(motorPitch[0], motorSpeed);
        analogWrite(motorPitch[1], 0);
}
void pitchStop(){
        analogWrite(motorPitch[0], 0);
        analogWrite(motorPitch[1], 0);
}
void flapPos(int motorSpeed){
        analogWrite(motorFlap[0], motorSpeed);
        analogWrite(motorFlap[1], 0);
}
void flapNeg(int motorSpeed){
```

```
        analogWrite(motorFlap[0], 0);
        analogWrite(motorFlap[1], motorSpeed);
}
void flapStop(){
        analogWrite(motorFlap[0], 0);
        analogWrite(motorFlap[1], 0);
}
void getU(){
        while (ss.available() > 0)
                gps.encode(ss.read());

        if (gps.speed.isUpdated()){
                Serial.println(gps.speed.kmph());
                if(gps.speed.mps() != 0)
                        U = gps.speed.mps();
                else U = StartSpeed;
        }
}
void setOmega(){
        if(motorEnc.read() - previousRead > 800){
                omega = 7.854*((motorEnc.read()-previousRead)/
                (millis()-previousOmegaTime));

                StOmega = St*U*17.453;

                if (omega > StOmega){
                        omegaValue--;
                }
                if (omega < StOmega){
                        omegaValue++;
                }
                Serial.println(omega);
                analogWrite(omegaPin, omegaValue);

                previousRead = motorEnc.read();
                previousOmegaTime = millis();
        }
        analogWrite(omegaPin, omegaValue);
}
void SDwrite(){
        SDcard = SD.open("results.txt", FILE_WRITE);
        if (SDcard) {
                SDcard.print(U);
                SDcard.print(" ; ");
                SDcard.print(omega);
```

```
                    SDcard.print(" ; ");
                    SDcard.print(Xforce.get_units());
                    SDcard.print(" ; ");
                    SDcard.print(Yforce.get_units());
                    SDcard.print(" ; ");
                    SDcard.println(t);
                    SDcard.close();
          }
}
```

C | Risk assessment

NTNU HMS	Kartlegging av risikofylt aktivitet	Utarbeidet av	Nummer	Dato
		HMS-avd.	HMSRV2601	22.03.2011
		Godkjent av		Erstatter
		Rektor		01.12.2006

Enhet: Institutt for maskinteknikk og produksjon **Dato:** 6.2.17

Linjeleder:

Deltakere ved kartleggingen (m/ funksjon): Ansv.veileder: Martin Steinert. Medveileder: John Martin Kleven Godø. Student: Jørgen Aasheim

Kort beskrivelse av hovedaktivitet/hovedprosess: Masteroppgave Jørgen Aasheim, "Hydrofoil prototype for oscillating hydrofoil propulsion".

Er oppgaven rent teoretisk? (JA/NEI): NEI

Signaturer: *Ansvarlig veileder:* *Student:*

ID nr.	Aktivitet/prosess	Ansvarlig	Eksisterende dokumentasjon	Eksisterende sikringstiltak	Lov, forskrift o.l.	Kommentar
1	Bruk av laserkutter	J.Aa.	Maskinens brukermanual	Opplæringskurs	Ukjent	
2	Bruk av 3D-printer	J.Aa.	Maskinens brukermanual	Ukjent	Ukjent	
3	Bruk av Dreiebenk og fres	J.Aa.	Maskinens brukermanual	Praksiskurs	Ukjent	
4	Bruk av sammenføyningsmidler	J.Aa.	Maskinens brukermanual	Datablad	Ukjent	
5	Eksperimentelt arbeid	J.Aa.	Egen risikovurdering må gjøres for hvert eksperiment		Prosessavhengig	
6	Tilstedeværelse ved arbeid utført av andre	Andre	Andres HMSRV2601	Andres HMSRV2601	Prosessavhengig	

NTNU	Risikovurdering	Utarbeidet av	Nummer	Dato
		HMS-avd.	HMSRV2601	22.03.2011
		Godkjent av		Erstatter
HMS		Rektor		01.12.2006

ID nr	Aktivitet fra kartleggings-skjemaet	Mulig uønsket hendelse/ belastning	Vurdering av sannsyn-lighet (1-5)	Vurdering av konsekvens: Menneske (A-E)	Ytre miljø (A-E)	Øk/ materiell (A-E)	Om-dømme (A-E)	Risiko-Verdi (menn-eske)	Kommentarer/status Forslag til tiltak
1a	Bruk av laserkutter	Klemskade	2	B	A	A	A	B2	Vær nøye med opplæring. Hold lokket igjen under bruk.
1b		Brannskade	2	B	A	A	A	B2	Vær nøye med opplæring. Bruk hansker ved håndtering av deler.
1c		Øyeskade	2	D	A	A	D	D2	Bruk øyevern.
1d		Brann	3	B	A	D	D	B3	Hold øye med maskinen under bruk. Ha slukkeutstyr tilgjengelig
2a	Bruk av 3D-printer	Brannskade	3	A	A	A	A	A3	Vær obs på deler som blir varme.
2b		Innhalering av avgasser	2	B	A	A	A	B2	Ikke stå over maskinen når den er I bruk.

NTNU HMS	Risikovurdering	Utarbeidet av	Nummer	Dato
		HMS-avd.	HMSRV2601	22.03.2011
		Godkjent av		Erstatter
		Rektor		01.12.2006

ID nr	Aktivitet fra kartleggings-skjemaet	Mulig uønsket hendelse/ belastning	Vurdering av sannsyn-lighet (1-5)	Vurdering av konsekvens: Menneske (A-E)	Ytre miljø (A-E)	Øk/ materiell (A-E)	Om-dømme (A-E)	Risiko-Verdi (menn-eske)	Kommentarer/status Forslag til tiltak
3a	Bruk av Dreiebenk og fres	Kuttskade	2	D	A	A	C	D2	Sørg for korrekt bruk. Alle deler/verktøy må være sikret
3b		Klemskade	2	D	A	A	C	D2	Unngå løse klesplagg
3c		Flygende spon/gjenstander	1	D	A	A	C	D1	Bruk øyevern. Dekk til roterende deler
4a	Bruk av sammenføyningsmidler	Eksponering øye	2	D	A	A	B	D2	Bruk øyevern.
4b		Eksponering hud	4	A	A	A	A	A4	Bruk hansker.
4c		Eksponering inhalering	4	B	A	A	A	B4	God ventilasjon. Bruk maske om nødvendig.

NTNU HMS	Risikovurdering	Utarbeidet av	Nummer	Dato
		HMS-avd.	HMSRV2601	22.03.2011
		Godkjent av		Erstatter
		Rektor		01.12.2006

ID nr	Aktivitet fra kartleggings-skjemaet	Mulig uønsket hendelse/ belastning	Vurdering av sannsyn-lighet (1-5)	Vurdering av konsekvens: Menneske (A-E)	Ytre miljø (A-E)	Øk/ materiell (A-E)	Om-dømme (A-E)	Risiko-Verdi (menn-eske)	Kommentarer/status Forslag til tiltak
5a	Eksperimentelt arbeid	Vann - drukning	1	E	A	A	E	E1	Vurdering må gjøres for hvert enkelt tilfelle
5b		Elektrisk støt	3	B	A	A	A	B3	Bruk isolert verktøy. Koble fra batteri under arbeid
		Elektriske komponenter i vann	3	A	A	B	A	A3	Sørg for at alt som skal være i kontakt med vann er vanntett
6	Tilstedeværelse ved arbeid utført av andre	Avhenger av hva som skal gjøres							Vurdering må gjøres for hvert enkelt tilfelle

Sannsynlighet vurderes etter følgende kriterier:

Svært liten 1	Liten 2	Middels 3	Stor 4	Svært stor 5
1 gang pr 50 år eller sjeldnere	1 gang pr 10 år eller sjeldnere	1 gang pr år eller sjeldnere	1 gang pr måned eller sjeldnere	Skjer ukentlig

Konsekvens vurderes etter følgende kriterier:

Gradering	Menneske	Ytre miljø Vann, jord og luft	Øk/materiell	Omdømme
E Svært Alvorlig	Død	Svært langvarig og ikke reversibel skade	Drifts- eller aktivitetsstans >1 år.	Troverdighet og respekt betydelig og varig svekket
D Alvorlig	Alvorlig personskade. Mulig uførhet.	**Langvarig skade. Lang restitusjonstid**	Driftsstans > ½ år Aktivitetsstans i opp til 1 år	Troverdighet og respekt betydelig svekket
C Moderat	Alvorlig personskade,	Mindre skade og lang restitusjonstid	Drifts- eller aktivitetsstans < 1 mnd	Troverdighet og respekt svekket
B Liten	Skade som krever medisinsk behandling	Mindre skade og kort restitusjonstid	Drifts- eller aktivitetsstans < 1uke	Negativ påvirkning på troverdighet og respekt
A Svært liten	Skade som krever førstehjelp	Ubetydelig skade og kort restitusjonstid	Drifts- eller aktivitetsstans < 1dag	Liten påvirkning på troverdighet og respekt

Risikoverdi = Sannsynlighet x Konsekvens
Beregn risikoverdi for Menneske. Enheten vurderer selv om de i tillegg vil beregne risikoverdi for Ytre miljø, Økonomi/materiell og Omdømme. I så fall beregnes disse hver for seg.

Til kolonnen "Kommentarer/status, forslag til forebyggende og korrigerende tiltak":
Tiltak kan påvirke både sannsynlighet og konsekvens. Prioriter tiltak som kan forhindre at hendelsen inntreffer, dvs. sannsynlighetsreduserende tiltak foran skjerpet beredskap, dvs. konsekvensreduserende tiltak.

NTNU	Risikomatrise	utarbeidet av	Nummer	Dato
		HMS-avd.	HMSRV2604	08.03.2010
		godkjent av		Erstatter
HMS/KS		Rektor		09.02.2010

MATRISE FOR RISIKOVURDERINGER ved NTNU

KONSEKVENS						
	Svært alvorlig	E1	E2	E3	E4	E5
	Alvorlig	D1	D2	D3	D4	D5
	Moderat	C1	C2	C3	C4	C5
	Liten	B1	B2	B3	B4	B5
	Svært liten	A1	A2	A3	A4	A5
		Svært liten	Liten	Middels	Stor	Svært stor
		SANNSYNLIGHET				

Prinsipp over akseptkriterium. Forklaring av fargene som er brukt i risikomatrisen.

Farge		Beskrivelse
Rød		Uakseptabel risiko. Tiltak skal gjennomføres for å redusere risikoen.
Gul		Vurderingsområde. Tiltak skal vurderes.
Grønn		Akseptabel risiko. Tiltak kan vurderes ut fra andre hensyn.

D | Project Thesis fall 2016

Learning to swim:
Generating concepts for a hydrofoil propulsion system

Jørgen Aasheim

December 2016

PROJECT THESIS
Department of Engineering Design and Materials
Norwegian University of Science and Technology

Supervisor: Professor Martin Steinert

Co-Supervisor: Ph.D. John Martin Kleven Godø

NTNU – Trondheim
Norwegian University of
Science and Technology

Abstract

Based on an ongoing development project at NTNU Technology Transfer this project has looked into concepts and solutions for using oscillating hydrofoils as a propulsion system for boats. This type of propulsion system can be said to come from biomimetics as it is heavy influence by how for example fish and dolphins swim.

Some prototyping has been done on different possibilities for mechanical solutions on how to drive the foils, and a test rig has been built. The test rig were to test the effect of using a movable flap at the end of the foil, this has previously been proven by others to be beneficial but for the sake of learning it was deemed to be a valuable use of time. As it turned out the test rig was not strong enough to give any readable data from the force meter but the it gave the author a better understanding of the concept of using oscillating hydrofoils for propulsion.

The most important part of this project has been gathering information on the subject and building up a foundation of knowledge before starting on the master thesis that will follow.

Preface

This report is the final result of a 9th semester specialization project at the Department of Engineering Design and Materials at NTNU. The idea for the project was presented by John Martin Kleven Godø from NTNU's Department of Marine Technology, and is based on work being done by him in collaboration with NTNU Technology Transfer. The project has been undertaken at the NTNU research laboratory TrollLabs, and its purpose is to lay the foundation for a master thesis.

Contents

Part I

Introduction

1 The report

This report has been divided into five parts:

Part I Introduction

A brief introduction to the project.

Part II Theory

Defines biomimetics and the hydro mechanical advantage of dolphins.

Gives a brief introduction to some of the concepts behind hydrofoil propulsion.

Part III Exploring concepts

Prototyping and research of topics related to the concept of hydrofoil propulsion.

Part IV Discussion and conclusion

Final thoughts into the subject and proposals for further work.

Part V Appendicies

Extra information on test setup used during research, the projects problem text and risk assessment.

2 The task

The given task was to generate and test concepts that would support "fish-like" propulsion. This was a very open challenge with many possible directions to take but after discussing with members of the ongoing development team a main focus of finding mechanical solutions for moving the foils were chosen. Bending hydrofoils were also deemed to be a interesting topic and should be researched if time allowed it.

As this is a concept heavy influenced by nature and the way fish and cetaceans swim it was also decided that some time would be spent studying biomimetics.

Part II

Theory

3 Biomimetics

3.1 Biomimetics

> "To put it simply, why not let evolution do your thinking for you?"

The words belong to Alan Rudolph(Taubes, 2000), who has worked with biomimetics for DARPA, and they shortly sum up the main idea behind the concept.

Biomimetics, or biomimicry as it is also called, is the study of how we can take ideas that nature have refined through thousands of years of evolution and apply them into new technology and innovation. This approach has in the past given us velcro which was inspired by burrs on seed pods that attach them selfs to animal fur and human clothing. And it has given neural networks a type of machine learning that mimics the building structure of the brain.(Sandhu, 2016)

Some of the earliest examples of biomimetics we find in aviation. Leonardo da Vinci studied the anatomy of birds when trying to create his flying machines and the Wright brothers studied the flight of pigeons when developing their airplane

3.2 Dolphins

Humans have yet to develop movement on water with efficiency that can match what we find in nature. Many studies have been done on swimming fish and maybe most famously by Sir James Gray whose study on dolphins came to be known as Gray's paradox(Gray, 1936). By using observations of

a dolphin swimming past a boat Gray was able to estimate a velocity of 20 knots or almost 40 km per hour. By assuming that the resistance the dolphin experience in the water is similar to that of a rigid body with the same size he was able to calculate that the dolphin outputted 2.6 horsepower. He compared this to studies done earlier on other mammals (humans and dogs) and how much horsepower they were able to output per unit mass of muscle. This indicated that in order for the dolphins to swim as fast as observations said they would need about 120kg of muscle, however a dolphin only has propulsive muscles of about 15kg. From this Gray hypothesized that there must be properties of the dolphins skin that drastically reduces their drag force in the water.

A study done in 2014 proves Gray's hypothesis to be wrong but shows that he was on to something interesting(Fish et al., 2014). The study used high-speed video cameras to film two bottlenose dolphins as they swam through an area of water that had been filled with thousands of small air bubbles. They where then able to use software to track the bubbles flow and its speed around the dolphins. From this they calculated the force the dolphins were able to generate with their tails to be 700N during small amplitude swimming and a staggering 1468N during large amplitude starts.

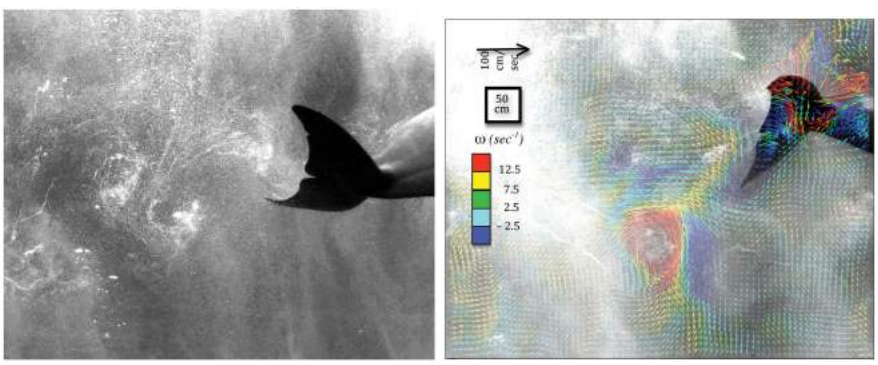


Figure 3.1: Pictures from bubble test taken from Fish et al. (2014)

The forces calculated is about 10 times stronger than what Gray hypothesized, more than enough to overcome the drag forces and obtain the velocities that have been observed. The study shows that the secret to the dolphins ability to achieve great velocities does not lie in its skin but instead may be in how it is shaped. Frank Fish, a biomechanist who worked on the bubble study, was quoted saying: "it basically starts to tell us things

about how well designed these aquatic athletes are. It could mean that flippered robots could theoretically be an alternative to the propeller-driven kind"(Khan, 2014).

4 Oscillating hydrofoil propulsion

4.1 Hydrofoils

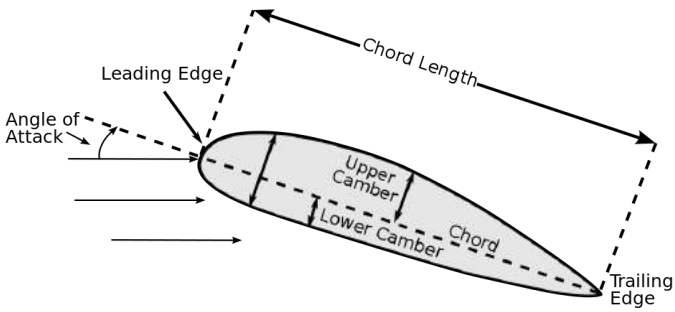


Figure 4.1: Foil terminology

A foil is an object that when placed in a fluid flow deflects the flow downwards and because of this produces a lifting force perpendicular to the incoming flow and a drag force parallel and in the same direction as the flow.(Weltner and Ingelman-Sundberg, 2003) (Anderson, 2011) The deflection of the flow is due to mainly the foils shape and angle between the flow and the foils chord line called angle of attack as shown in figure 4.1.

Foils are typically named after what type of fluid they operate in. If the fluid is a gas they are called airfoils and if the fluid is water as the case in this report they are called hydrofoils. A foil is a section of a wing but it is not uncommon to hear the entire wing be referred to as a foil and this will also be used in this report.

4.2 Oscillating foils

As mentioned in section 3.2 flapping foils could be a good alternative to the more traditional propeller. In an experiment done at Massachusetts Institute of Technology(Triantafyllou and Triantafyllou, 1995) the Strouhal number of both fish and previous flapping foil experiments was calculated. The Strouhal number is a dimensionless number that describes oscillating flow. It tells how often vortices are created by the flapping and how close they are to each other.

$$St = \frac{fL}{U} \tag{4.1}$$

St - Strouhal number
f - Frequency of tail/foil flapping
L - Travel length of tail/foil
U - Speed fish/foil

What they found was that all fish swing their tail with a Strouhal number that lies between 0.25 and 0.35. Earlier experiments with flapping foils that had reported bad efficiency turned out to have Strouhal numbers that were nowhere close to this range. After adjusting their foils to operate in the range they where able measure efficiencies higher than 86 percent. Small propellers typically get about 40 percent.

Looking at the tails of some of the fastest swimming animals one can see that they closely resemble high-aspect-ratio foils(Anderson et al., 1998). The biggest difference being that foils typically do not bend like the tails do.

4.3 Trailing edge flap

A flap at the trailing edge of the foil gives the option to vary the camber. By adjusting the camber to the up and down motion the water is deflected in the opposite direction that thrust is wanted and the need for a large angle of attack is decreased.

Part III

Exploring concepts

5 Moving the foils

The hydrofoils movement can be divided into three as is shown in figures 5.1, 5.2 and 5.3. They can move up and down, rotate and angle the trailing edge flap.

When exploring different mechanical concepts it became clear that they could be divided into two categories: One where all three movements operate independently and one where they are locked in one movement pattern.

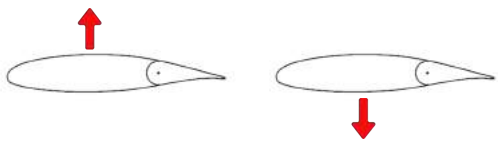


Figure 5.1: Up and down motion

Figure 5.2: Foil rotation

Figure 5.3: Flap angle

5.1 One degree of freedom

5.1.1 Slider crank

Figure 5.4: Slider crank prototype.

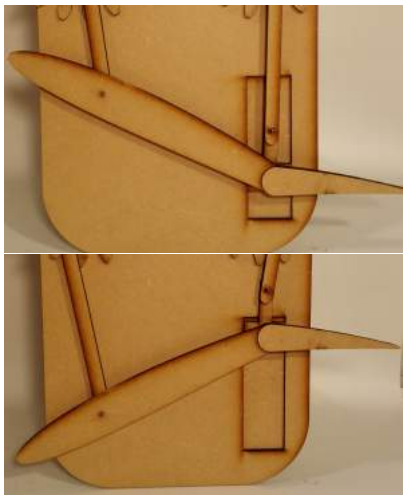


Figure 5.5: Shifting angle.

The slider crank prototype is a "2D representation" of the concept. Two gears driven by a third gear moves a foil with slider arms. The arm moving the rear end of the foil is locked in a slider that can only move up and down and the flap is attached perpendicular to the slider. This insures that the flap is always pointing backwards as the foil moves up and down as can be seen in figure 5.5. The slider arms are attaches to their gears with an offset relative to each other so that when moving the foil's angle shifts.

5.1.2 Parallelogram linkage

Figure 5.6: The linkage bar keeps the flap pointing backwards

The prototype shown in figure 5.6 was built as one of the foils for the testing rig that will be discussed in chapter 8. The foil's front mounting point, the flaps hinge and the lower linkage bar forms a parallelogram. Because the distances is kept constant the "lines" stays parallel when the angles are varied. This keeps the foil's flap always pointing backwards.

The extra mechanical parts exposed to the water does increase drag and therefor it would be beneficial to move the mechanism inside the foil.

5.2 Three degrees of freedom

5.2.1 Internal flap mechanism

In section 5.1.2 the foil's angle was changed while the angle of the flap was kept constant by pushing one of the parallelogram's corners down. If instead one of the corners where pushed sideways, perpendicular to the movement

in section 5.1.2, the angle of the foil would be kept constant and the flap would move. That way the two movements are made independent of each other.

Figure 5.7: Internal flap mechanism

Figure 5.7 shows the prototype. There are two axles, one inside the other. The foil's main body is attached to the outer axle and the inner axle turns the flap.

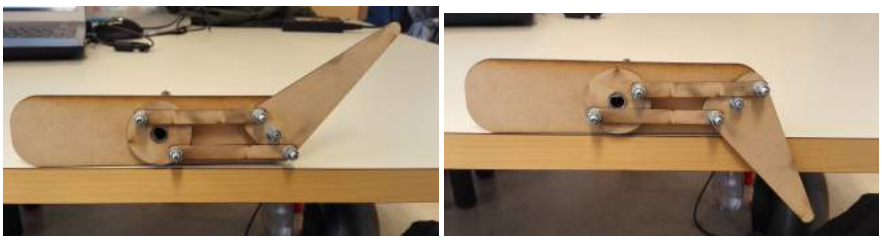


Figure 5.8: Rotating the inner axle turns the flap.

5.2.2 Rack and pinion

This section will add to the prototype in 5.2.1 by including a way to control the rotations of the axles when the foil moves up and down.

Gears have been added to the axles as shown in figure 5.10. The gears are connected to gear racks, and the racks are connected to linear bearings in figure 5.11 that slides on shafts. It is not shown in any of the figures but the shafts are imagined to be attached in each end to additional linear bearings that can slide from side to side perpendicular to the shaft shown in the figure. Because of this the gear mechanism can move freely up and down and when the shaft is moved from side to side the bearing pushes the rack which turns the gear.

Figure 5.9: Up and down motion added to prototype from 5.2.1.

Figure 5.10: Gear and pinion to move axles.

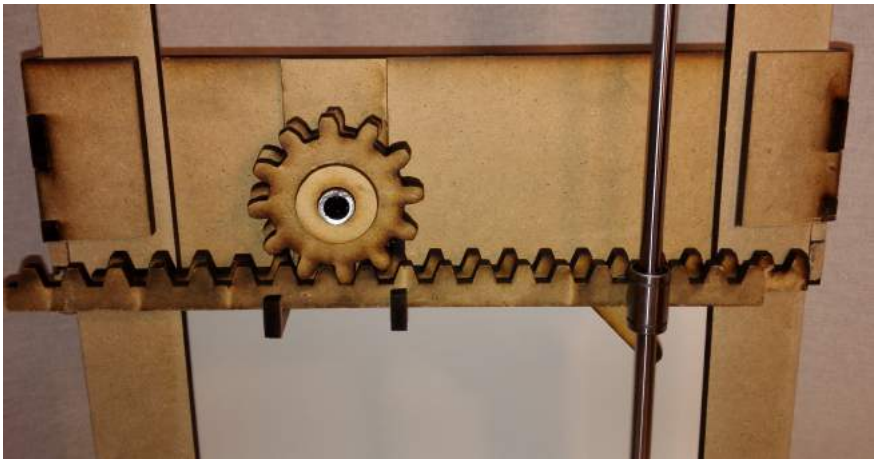


Figure 5.11: Mechanism for turning foil and flap.

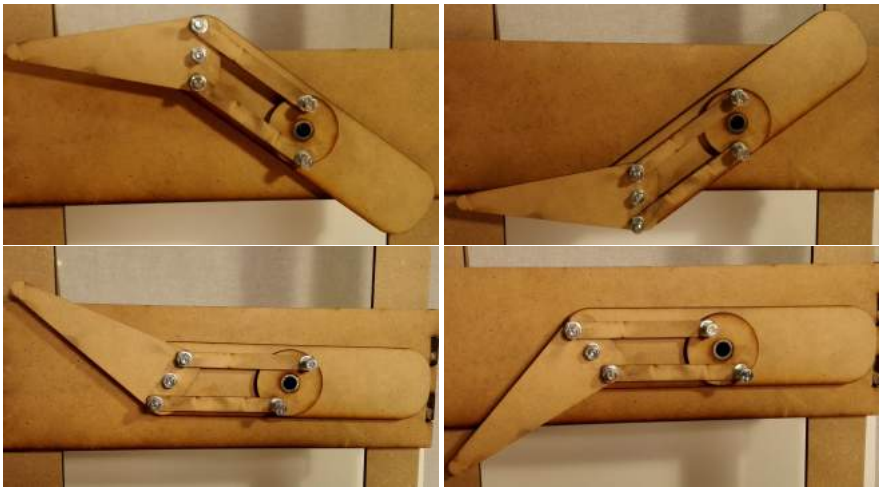


Figure 5.12: Three degrees of freedom.

5.3 Powering the movements

5.3.1 Motors inside foil

The prototypes in the sections above area all based on having the motors on the boat, another option would be to have electric motors built into the foils. There are several advantages to this, one being that it simplifies the need for mechanical transfer of power. It would also lower the boats center of mass making it more stable as well as freeing up space on the boat.

A challenge would be transferring power and electric signals from the boat to the motors. Slip rings, also known as electric rotary joints, could be used inside the foil and a cable carriers could be used to follow the foils up and down motion.

5.3.2 Hydraulics

Another way of powering the foils that may be beneficial is with a hydraulics system. Hydraulics are great at moving heavy loads and can give precise movements(Savela, 2011). It would also be beneficial if looked at from the perspective of power saving because instead of using several electrical motors to power each movement one motor could power a hydraulics pump that again power several motion axes. By using accumulators to vary the power output as needed the motor running the pump can keep a constant speed and the need for gearing is therefore eliminated.

6 Bending hydrofoil

The trailing edge flaps makes the hydrofoils more effiecient but the hard edge between the foils body and the flap are not ideal. It would be better if the foils would bend more like the tails of fish, dolphins and whales.

Figure 6.1: Picture of humpback whale tail, taken from Parry (2012)

There have been some work done on the subject but to the authors knowledge this has been mainly in aerospace(Chandler, 2016)(Philen, 2016)(Sridhar et al., 2006). Examples are shown in figures 6.2, 6.3 and 6.4

Figure 6.2: Taken from Chandler (2016)

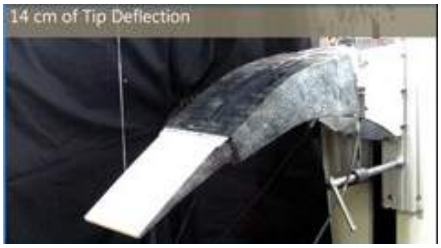


Figure 6.3: Taken from Philen (2016)

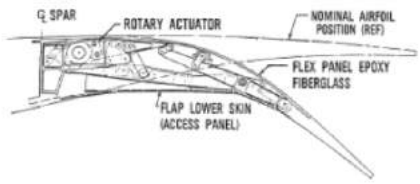


Figure 6.4: Taken from Sridhar et al. (2006)

7 Machine learning

This chapter was originally written as a paper for the course TMM4280 - Advanced Product Development, the task was to write a project proposal for applying machine learning to some situation in an imagined company. The paper is a proposal for using machine learning to find the best way to move a hydrofoil propulsion system on a boat.

7.1 What is machine learning

Machine learning(ML) is the process of letting computers learn by them self without being explicitly programmed to do a specific task. ML can be divided into three categories, these are:

Supervised learning: The computer is given labeled data that shows examples of input and their desired output. From this the computer makes models that tries to guess the right output when given input.

Unsupervised learning: Here the computer is given unlabeled data and will try to categorize it. This is also a good way to discover hidden patterns in the data.

Reinforcement learning: The computer is given a goal which it must achieve in the environment it operates. Examples of how reinforcement learning has been used is driving a car around a track or playing a video game. Typically the computer is given points depending on how close it comes to the goal and how fast.

7.2 Possible solution

By applying reinforcement learning to the ships hydrofoil propulsion system it might be possible to discover a more effective movement pattern than the one we use today.

The moving hydrofoils have three degrees of freedom: Up and down, rotate, and flap rotation. These all move independent of each other. These three movements would be the set of actions that the system have to choose between and after performing a random set of actions the computer is given a score based on how close it got to its target and how fast. It does this over and over basing each new set on what gave it a higher score earlier and adding variations.

The target will in the beginning, based on the present simplicity of the propulsion system, only be to travel in a straight line. But as the mechanical system becomes more advanced it will be beneficial to have the goal be finishing some sort of obstacle course.

Based on this process of trial and error the computer builds up a dataset which it can use to determine what movements are most beneficial.

7.3 Benefits and challenges

The benefit of applying this, if successful, would be a better more effective propulsion system for the hydrofoil driven ships. The sea is hard to model and it is likely that an oscillating foil is not the optimal solution. ML might be the most effective way at finding the most effective movement.

However is should also be noted that the process is time consuming. Gathering data and letting the system randomly try out movements until successful will take a long time. But one can argue that if the goal is to find the most effective movement this is the fastest solution.

7.4 Conclusion

When it comes to foil propulsion on ships it is hard to determine what it most effective because the motion takes place in an environment that is hard to model. By applying reinforcement learning, a type of machine learning,

a computer can test out different types of randomly chosen foil movements. It can then based on data from these tests decide upon the most effective one.

It is uncertain if this will result in a more effective foil movement, but it is very likely that if there exists a more effective movement this is the most effective way to discover it.

8 Testing

To better understand the concept of using oscillating foils for propulsion a testing rig with two foils was built. The purpose was to see if a difference in thrust could be measured between a foil with a flap and one without.

8.1 The rig

Figure 8.1: The testing rig

The rig is a simple frame with floaters on each side. DC motors and drawer sliders fitted with a rack and pinion form linear actuators that can drive the

foils up and down(Figure 8.2). Two servo motors are used to adjust the angle of the foils(Figure 8.3).

Figure 8.2: Motors on each side provide up and down motion

Figure 8.3: Servomotors for adjusting foil angles

Figure 8.4: Limit switches mark endpoints of motion

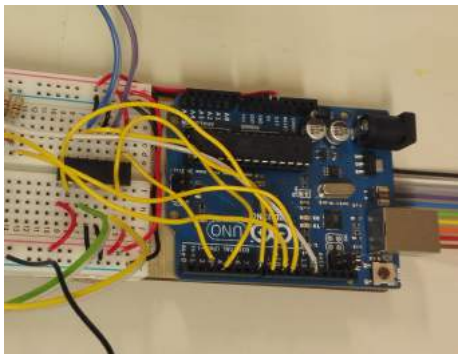


Figure 8.5: An Arduino was used to control the rig

Limit switches are used to control the endpoints of the motion. Everything is controlled by an Arduino.

Schematics for the electronics can be found in appendix A and Arduino code in appendix B.

8.2 The foils

The foils were based on the profile NASA LS413(airfoiltools, 2016). They have a chord length of 100mm, max camber is 13%(13mm), and they have a span of 500mm.

Figure 8.6: Both foils before wrapping

Figure 8.7: Foil test fitting in test rig

Figure 8.8: Both foils after wrapping

They were built by laser cutting the basic structure in MDF, as can be seen in figure 8.6, and wrapped in durable tape to give them the right form. The final foils can be seen in figure 8.8.

8.3 Testing

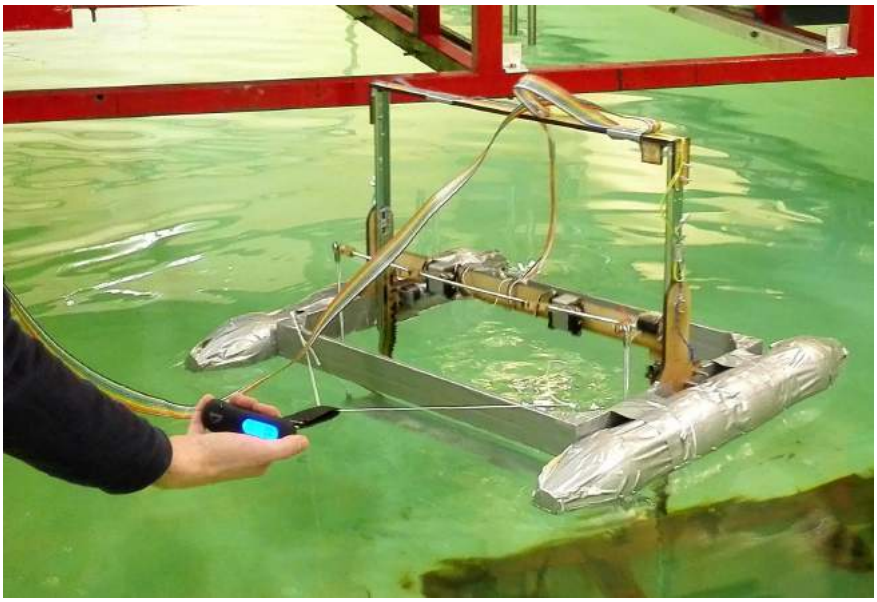


Figure 8.9: Measuring thrust

To measure the thrust the rig was attached to a force meter as shown in figure 8.9. The two foils where to be tested at different angles of attack. Unfortunately the motors were not strong enough to give a force that could be registered by the meter therefore no data was collected during testing. Just by looking at the rig it did seem to move faster when using the foil with a flap but this is only speculation.

After finishing the planned test some time was spent dragging the foils through the water by hand. Shown in figure 8.10. This gave surprising insight into how foil propulsion works because one could feel how the foil pulled it self forwards in the water.

Figure 8.10: Hands on experience.

Part IV

Discussion and conclusion

9 Discussion and conclusion

This project has looked at concepts and solutions around a boat propulsion system inspired by the way fish and cetaceans swim, and it has been established that this way of finding inspiration for innovation in nature is known as biomimetics. Even though the initial idea came from nature the development process has not tried to exactly copy nature and this is not the purpose of biomimetics. In that way biomimetics can be said to be a tool for inspiration not product development.

The hydrofoils where defined to have three degrees of freedom and during prototyping both designs that allowed for independently moving each one and designs that locked them together in one movement were considered. At this stage it is uncertain which type would be most beneficial but it is possible that other movements than the standard oscillation will be needed and therefore a design that allows for independent movement should be chosen.

The foils can be powered either from motors in the boat or motors that are built into the foils. It would seem than building motors into the foils are preferable as it gives a simpler mechanical system, and it will give a more stable boat as the center of mass is lowered. There are also indications that hydraulics could be a good alternative to electric motors but too little research has been done at this point.

There is a lot more work needed to be done before a finished concept can be built and this project has only lightly touched on a vast subject. The most important outcome of the project is not prototypes or hydrofoil propulsion concepts but basic knowledge needed by the author for the master thesis.

10 Proposals for further work

There is still a lot more work to be done developing a working mechanical system. The conclusions in this report can be used as a starting point for further development but they should in no way be used as established truths. There are also other aspects not taken into consideration in this report that needs to be, for example the option to retract the propulsion system when entering shallow water and harbors. There will also be a need for steering which probably can find inspiration from nature as the propulsion system did.

Keeping with the biomimetics theme better hydrofoils should be made based on for example dolphin tails. Some sort of compliant mechanism which allows the foil to bend elastically giving it a smoother curve could be very beneficial.

Some material suggesting that hydraulics could be a better alternative than electric motors were found but this is very uncertain at this point. Looking into the possibility of using a hydraulic system, how it should be designed and the possible energy savings might prove to be useful.

At some point a test boat should be built that allows for testing the system under real conditions but some work remains before this can be done. However an early prototype could prove valuable in discovering potential unknown unknowns and it could serve as a platform for applying machine learning to the problem.

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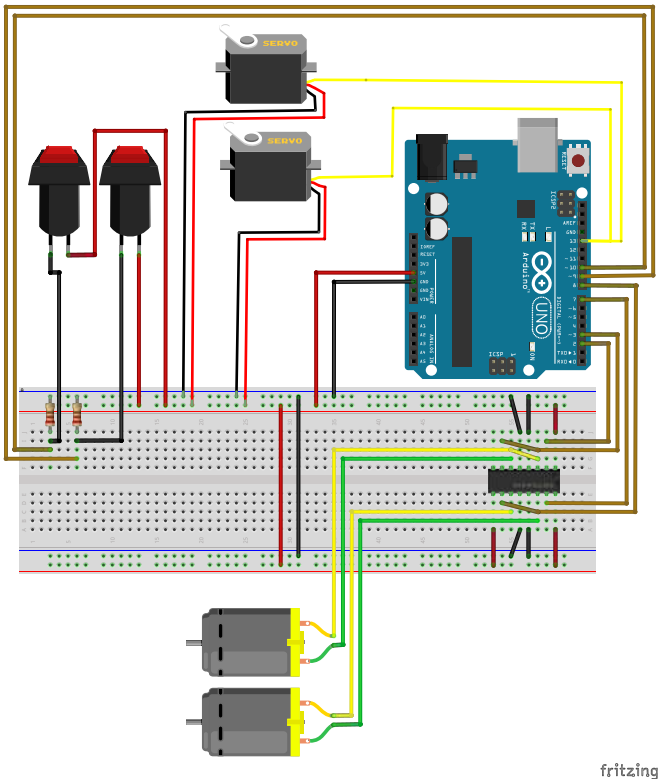
Part V

Appendices

A Test rig electronics

Figure showing how to connect electronics for testing rig.
A 24 volts power supply should also be attached to the 8th leg of the H-bridge.



B | Arduino code

```
int motor_left[] = {2, 3};
int motor_right[] = {7, 8};

#include <Servo.h>
Servo myservo;

int pos = 90;     // adjust foils zero point

int knappNederst = 10;
int knappOverst = 9;
int nederst = 0;
int overst = 0;


int alpha = 30; // Foil angle

void setup() {

        int i;
        for (i = 0; i < 2; i++){
                pinMode(motor_left[i], OUTPUT);
                pinMode(motor_right[i], OUTPUT);
        }

        myservo.attach(13);

        pinMode(knappNederst, INPUT);
        pinMode(knappOverst, INPUT);
```

```
}

//////////////////////////////////////////////////LOOP
void loop() {

        nederst = digitalRead(knappNederst);
        overst = digitalRead(knappOverst);

        drive();

        //myservo.write(90);

}//////////////////////////////////////////////////LOOP

void drive(){
        if (nederst == HIGH){
                opp();
                myservo.write(pos+alpha-7);
        }
        if (overst == HIGH){
                ned();
                myservo.write(pos-alpha+7);
        }
}

void motor_stop(){
        digitalWrite(motor_left[0], LOW);
        digitalWrite(motor_left[1], LOW);

        digitalWrite(motor_right[0], LOW);
        digitalWrite(motor_right[1], LOW);
}

void ned(){
        digitalWrite(motor_left[0], LOW);
        digitalWrite(motor_left[1], HIGH);

        digitalWrite(motor_right[0], HIGH);
        digitalWrite(motor_right[1], LOW);
}
```

```
void opp(){
        digitalWrite(motor_left[0], HIGH);
        digitalWrite(motor_left[1], LOW);

        digitalWrite(motor_right[0], LOW);
        digitalWrite(motor_right[1], HIGH);
}
```

C | Problem text

THE NORWEGIAN UNIVERSITY
OF SCIENCE AND TECHNOLOGY
DEPARTMENT OF ENGINEERING DESIGN
AND MATERIALS

PROJECT WORK FALL 2016
FOR
STUD.TECHN. Jørgen Aasheim

Swimming boats, fishlike propulsion

The challenge is to generate and test concepts and solutions that support fishlike propulsion systems

- generate concepts
- build prototypes
- build test setups
- test and compare alternatives
- synthesize into propulsion concept
- judge and evaluate concept

Also, it is expected to contribute to one or more scientific publications during the project/master thesis.
The supporting coach is John Martin Godø from Marine Tech/Tyholt.

Formal requirements:

Students are required to submit an A3 page describing the planned work three weeks after the project start as a pdf-file via "IPM DropIT" (http://129.241.88.67:8080/Default.aspx). A template can be found on IPM's web-page (https://www.ntnu.edu/ipm/project-and-specialization).

Performing a risk assessment is mandatory for any experimental work. Known main activities must be risk assessed before they start, and the form must be handed in within 3 weeks after you receive the problem text. The form must be signed by your supervisor. Risk assessment is an ongoing activity, and must be carried out before starting any activity that might cause injuries or damage materials/equipment or the external environment. Copies of the signed risk assessments have to be put in the appendix of the project report.

No later than 1 week before the deadline of the final project report, you are required to submit an updated A3 page summarizing and illustrating the results obtained in the project work.

Official deadline for the delivery of the report is 13 December 2016 at 2 p.m. The final report has to be delivered at the Department's reception (1 paper version) and via "IPM DropIT".

When evaluating the project, we take into consideration how clearly the problem is presented, the thoroughness of the report, and to which extent the student gives an independent presentation of the topic using his/her own assessments.

The report must include the signed problem text, and be written as a scientific report with summary of important findings, conclusion, literature references, table of contents, etc. Specific problems to be addressed in the project are to be stated in the beginning of the report and briefly discussed. Generally the report should not exceed thirty pages including illustrations and sketches.

Additional tables, drawings, detailed sketches, photographs, etc. can be included in an appendix at the end of the thirty page report. References to the appendix must be specified. The report should be presented so that it can be fully understood without referencing the Appendix. Figures and tables must be presented with explanations. Literature references should be indicated by means of a number in brackets in the text, and each reference should be further specified at the end,of the report in a reference list. References should be specified with name of author(s) and book, title and year of publication, and page number.

Contact persons:
At the department: Martin Steinert
From Marine: John Martin Godø

Martin Steinert
Supervisor

NTNU
Norges teknisk-naturvitenskapelige universitet
Institutt for produktutvikling og materialer

D | Risk assessment

NTNU HMS	Kartlegging av risikofylt aktivitet	Utarbeidet av	Nummer	Dato
		HMS-avd.	HMSRV2601	22.03.2011
		Godkjent av		Erstatter
		Rektor		01.12.2006

Enhet: Institutt for produktutvikling og materialer **Dato:**

Linjeleder:

Deltakere ved kartleggingen (m/ funksjon)**:** Ansv.veileder: Martin Steinert. Medveileder: John Martin Kleven Godø. Student: Jørgen Aasheim

Kort beskrivelse av hovedaktivitet/hovedprosess: Prosjektoppgave Jørgen Aasheim, "Swimming boats, fishlike propulsion".

Er oppgaven rent teoretisk? (JA/NEI): NEI

Signaturer: *Ansvarlig veileder:* *Student:*

ID nr.	Aktivitet/prosess	Ansvarlig	Eksisterende dokumentasjon	Eksisterende sikringstiltak	Lov, forskrift o.l.	Kommentar
1	Bruk av laserkutter	J.Aa.	Maskinens brukermanual	Opplæringskurs	Ukjent	
2	Bruk av 3D-printer	J.Aa.	Maskinens brukermanual	Ukjent	Ukjent	
3	Bruk av Dreiebenk og fres	J.Aa.	Maskinens brukermanual	Praksiskurs	Ukjent	
4	Bruk av sammenføyningsmidler	J.Aa.	Maskinens brukermanual	Datablad	Ukjent	
5	Eksperimentelt arbeid	J.Aa.	Egen risikovurdering må gjøres for hvert eksperiment		Prosessavhengig	
6	Tilstedeværelse ved arbeid utført av andre	Andre	Andres HMSRV2601	Andres HMSRV2601	Prosessavhengig	

NTNU	Risikovurdering	Utarbeidet av	Nummer	Dato
		HMS-avd.	HMSRV2601	22.03.2011
		Godkjent av		Erstatter
HMS		Rektor		01.12.2006

ID nr	Aktivitet fra kartleggings-skjemaet	Mulig uønsket hendelse/ belastning	Vurdering av sannsyn-lighet	Vurdering av konsekvens:				Risiko-Verdi (menn-eske)	Kommentarer/status Forslag til tiltak
			(1-5)	Menneske (A-E)	Ytre miljø (A-E)	Øk/ materiell (A-E)	Om-dømme (A-E)		
1a	Bruk av laserkutter	Klemskade	2	B	A	A	A	B2	Vær nøye med opplæring. Hold lokket igjen under bruk.
1b		Brannskade	2	B	A	A	A	B2	Vær nøye med opplæring. Bruk hansker ved håndtering av deler.
1c		Øyeskade	2	D	A	A	D	D2	Bruk øyevern.
1d		Brann	3	B	A	D	D	B3	Hold øye med maskinen under bruk. Ha slukkeutstyr tilgjengelig
2a	Bruk av 3D-printer	Brannskade	3	A	A	A	A	A3	Vær obs på deler som blir varme.
2b		Innhalering av avgasser	2	B	A	A	A	B2	Ikke stå over maskinen når den er I bruk.

ID nr	Aktivitet fra kartleggings-skjemaet	Mulig uønsket hendelse/ belastning	Vurdering av sannsyn-lighet	Vurdering av konsekvens:				Risiko-Verdi (menn-eske)	Kommentarer/status Forslag til tiltak
			(1-5)	Menneske (A-E)	Ytre miljø (A-E)	Øk/ materiell (A-E)	Om-dømme (A-E)		
3a	Bruk av Dreiebenk og fres	Kuttskade	2	D	A	A	C	D2	Sørg for korrekt bruk. Alle deler/verktøy må være sikret
3b		Klemskade	2	D	A	A	C	D2	Unngå løse klesplagg
3c		Flygende spon/gjenstander	1	D	A	A	C	D1	Bruk øyevern. Dekk til roterende deler
4a	Bruk av sammenføyningsmidler	Eksponering øye	2	D	A	A	B	D2	Bruk øyevern.
4b		Eksponering hud	4	A	A	A	A	A4	Bruk hansker.
4c		Eksponering inhalering	4	B	A	A	A	B4	God ventilasjon. Bruk maske om nødvendig.

ID nr	Aktivitet fra kartleggings-skjemaet	Mulig uønsket hendelse/ belastning	Vurdering av sannsyn-lighet	Vurdering av konsekvens:				Risiko-Verdi (menn-eske)	Kommentarer/status Forslag til tiltak
			(1-5)	Menneske (A-E)	Ytre miljø (A-E)	Øk/ materiell (A-E)	Om-dømme (A-E)		
5a	Eksperimentelt arbeid	Vann - drukning	1	E	A	A	E	E1	Vurdering må gjøres for hvert enkelt tilfelle
5b		Elektrisk støt	3	B	A	A	A	B3	Bruk isolert verktøy. Koble fra batteri under arbeid
		Elektriske komponenter i vann	3	A	A	B	A	A3	Sørg for at alt som skal være I kontakt med vann er vanntett
6	Tilstedeværelse ved arbeid utført av andre	Avhenger av hva som skal gjøres							Vurdering må gjøres for hvert enkelt tilfelle

Sannsynlighet vurderes etter følgende kriterier:

Svært liten 1	Liten 2	Middels 3	Stor 4	Svært stor 5
1 gang pr 50 år eller sjeldnere	1 gang pr 10 år eller sjeldnere	1 gang pr år eller sjeldnere	1 gang pr måned eller sjeldnere	Skjer ukentlig

Konsekvens vurderes etter følgende kriterier:

Gradering	Menneske	Ytre miljø Vann, jord og luft	Øk/materiell	Omdømme
E **Svært Alvorlig**	Død	Svært langvarig og ikke reversibel skade	Drifts- eller aktivitetsstans >1 år.	Troverdighet og respekt betydelig og varig svekket
D **Alvorlig**	Alvorlig personskade. Mulig uførhet.	Langvarig skade. Lang restitusjonstid	Driftsstans > ½ år Aktivitetsstans i opp til 1 år	Troverdighet og respekt betydelig svekket
C **Moderat**	Alvorlig personskade.	Mindre skade og lang restitusjonstid	Drifts- eller aktivitetsstans < 1 mnd	Troverdighet og respekt svekket
B **Liten**	Skade som krever medisinsk behandling	Mindre skade og kort restitusjonstid	Drifts- eller aktivitetsstans < 1uke	Negativ påvirkning på troverdighet og respekt
A **Svært liten**	Skade som krever førstehjelp	Ubetydelig skade og kort restitusjonstid	Drifts- eller aktivitetsstans < 1dag	Liten påvirkning på troverdighet og respekt

Risikoverdi = Sannsynlighet x Konsekvens
Beregn risikoverdi for Menneske. Enheten vurderer selv om de i tillegg vil beregne risikoverdi for Ytre miljø, Økonomi/materiell og Omdømme. I så fall beregnes disse hver for seg.

Til kolonnen "Kommentarer/status, forslag til forebyggende og korrigerende tiltak":
Tiltak kan påvirke både sannsynlighet og konsekvens. Prioriter tiltak som kan forhindre at hendelsen inntreffer, dvs. sannsynlighetsreduserende tiltak foran skjerpet beredskap, dvs. konsekvensreduserende tiltak.

NTNU	Risikomatrise	utarbeidet av	Nummer	Dato	
		HMS-avd.	HMSRV2604	08.03.2010	
		godkjent av		Erstatter	
HMS/KS		Rektor		09.02.2010	

MATRISE FOR RISIKOVURDERINGER ved NTNU

KONSEKVENS	Svært alvorlig	E1	E2	E3	E4	E5
	Alvorlig	D1	D2	D3	D4	D5
	Moderat	C1	C2	C3	C4	C5
	Liten	B1	B2	B3	B4	B5
	Svært liten	A1	A2	A3	A4	A5
		Svært liten	Liten	Middels	Stor	Svært stor
		SANNSYNLIGHET				

Prinsipp over akseptkriterium. Forklaring av fargene som er brukt i risikomatrisen.

Farge		Beskrivelse
Rød		Uakseptabel risiko. Tiltak skal gjennomføres for å redusere risikoen.
Gul		Vurderingsområde. Tiltak skal vurderes.
Grønn		Akseptabel risiko. Tiltak kan vurderes ut fra andre hensyn.