A Bio-Inspired Oscillating Underwater Fin for Generating Water Movement that Saves Plankton and Fish Larvae

Realizing minimum input and maximum thrust by mimicking nature

Menno Bas

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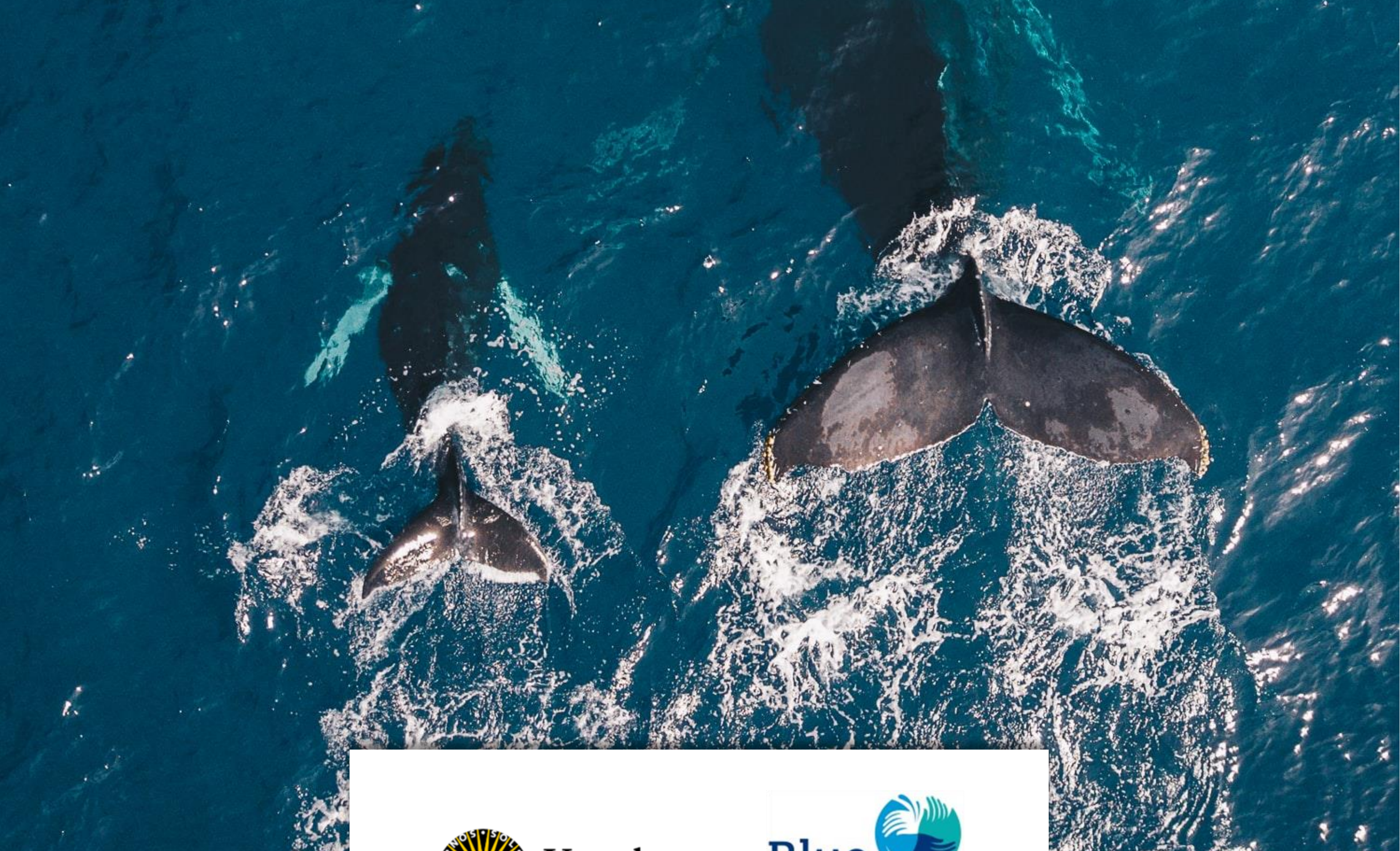
Final Report



Utrecht University

Blue linked

Cover photo:

Guille Pozzi, 2018, mother and calf humpback whales (*Megaptera novaeangliae*) in the Pacific Ocean near the island of Maui (Hawaii, USA), via Unsplash.
This species is of special significance to the author of this thesis, since this is the whale species that sparked his interest in bio-inspired innovation through the whale-inspired wind turbines (whalepowercorp.wordpress.com).

Student: Menno Bas
Student ID: 6275273
Email address: m.c.h.bas@students.uu.nl
Master of Science in Bio-Inspired Innovation (MSc BII), Utrecht University (UU)

Examiner: Prof. Dr. Leo Maas
Position: Associate Professor in Fluid Dynamics at UU
Email address: l.r.m.maas@uu.nl
Physical Oceanography, Institute for Marine and Atmospheric research Utrecht (IMAU)

Supervisor: Michaël Laterveer
Position: Senior Marine Researcher and Managing Director at BlueLinked
Email address: m.laterveer@bluelinked.nl

Second supervisor: Dr. Jaco Appelman
Position: MSc BII Lecturer/Coordinator at UU, Graduate School of Life Sciences (GSLS)
Email address: j.h.appelman@uu.nl

Abstract

Realizing minimum input and maximum thrust by mimicking nature is the foundation of bio-inspired innovation. At BlueLinked, a unique Dutch company in the marine aquaculture, innovations are created inspired by nature and realized by science. BlueLinked is developing an on-land circular method for fish farming. In these “TinyOceans” fish larvae can grow up efficiently and in their natural ecosystem. The fish larvae and the plankton species in their food chain are fragile and hard to keep alive. Turbulent water, resulting from the commonly used flow generators, is one of the leading causes of death of these small organisms. The question of how to generate water movement without disrupting plankton and fish larvae is examined. The product of natural evolution is used to create this structured and laminar-like flow. The different shapes and chord lengths of the developed oscillating underwater fins were based on the tail fins and swimming kinematics of several whale species. Moreover, the stiffness of real porpoise flukes was determined and mimicked in self-made prototypes. Comparing the fluid dynamics of each prototype in the water column to the energy used provided answers to whether the biomimetic design outperforms the custom mechanical way of creating a water flow. This pioneering research at the breeding center of BlueLinked aims to contribute to the movement of efficient and sustainable marine aquaculture that we need in this changing world.

Keywords: biomimicry/biomimetics, hydrodynamics, cetaceans, marine aquaculture, circularity

Layman’s Summary (ENG)

The global human population is growing and so is the demand for food. At the same time, climate change and the loss of biodiversity is an increasing problem. The company BlueLinked is developing a saltwater fish farm on land, efficiently breeding both new wild fish and fish for consumption with the motto “*one fish on your plate and one fish in the sea*”. In big specially designed tanks, a tiny natural sea is mimicked. Here, small fish larvae are raised. To make the conditions as natural as possible, live algae and small food organisms are kept in the same tank. Everything is completely in balance. With this, the fish larvae are surrounded by their diet and the right size of food is available at all times. It is important that the water in the tank remains well mixed. A normal flow pump is not suitable for this, because it causes a lot of turbulence. The fish larvae and other small organisms are very vulnerable and will not survive this wild water.

This project investigated how a water flow can be created that leaves the fragile organisms in the water intact. This is done inspired by nature. As a result of millions of years of evolution, only the best functioning mechanisms in nature have been preserved. The tail fin of a whale is such a highly developed product of natural selection. Whales can swim very smoothly and efficiently through the water thanks to their tail fin. Its shape and flexibility ensure that the drag and pressure of the water are used in advantage for the movement through the water, using minimal energy. Prototypes have been made based on three different shapes of tail fins, which can be attached to a special device that moves vertically up and down above the breeding tank. The experiments conclude that the underwater fin based on the gray whale’s tail fin can is the most efficient in creating a proper flow. This oscillating fin is now used to create with minimal electricity needs a calm propulsive current in the breeding tanks at BlueLinked, in which all tiny organisms can survive. Inspired by nature and realised by science, the problem has been solved and a contribution is made to sustainable fish farming.

Lekensamenvatting (NL)

De wereldbevolking groeit en daarmee ook de behoefte aan voedsel. Tegelijkertijd is klimaatverandering en het verlies aan biodiversiteit een steeds erger wordend probleem. Bij het bedrijf BlueLinked wordt een zoutwater vissenboerderij op het land ontwikkeld, waarmee zowel nieuwe wilde vissen als vissen voor consumptie efficiënt worden gekweekt onder het motto “*één vis op je bord en één vis in de zee*”. In grote speciaal ontworpen bakken wordt een stukje natuurlijke zee nagebootst. Hierin worden kleine vissenlarven opgekweekt. Om de omstandigheden zo natuurlijk mogelijk te maken, worden levende algen en voedseldiertjes gehouden in dezelfde bak. Alles is volledig in balans met elkaar. Hiermee zwemmen de vissenlarven midden tussen hun eten en is er op elk moment het juiste formaat voedsel beschikbaar. Het is belangrijk dat het water in de bak goed gemixt blijft. Een normale stromingspomp is alleen niet geschikt, omdat het veel turbulentie veroorzaakt. De vissenlarven en kleine voedseldiertjes zijn heel kwetsbaar en overleven dit wilde water niet.

In dit project is onderzocht hoe er een waterstroming gemaakt kan worden die de fragiele organismen in het water intact laat. Hiervoor is inspiratie opgedaan uit de natuur. Als gevolg van miljoenen jaren aan evolutie zijn alleen de best werkende mechanismen in de natuur behouden. Een walvisstaartvin is zo een ver ontwikkeld product van natuurlijke selectie. Walvissen kunnen heel rustig en efficiënt door het water zwemmen met dank aan hun staartvin. De vorm en flexibiliteit hiervan zorgen ervoor dat de weerstand en druk van het water juist in het voordeel worden gebruikt om door het water te bewegen met minimale energiebehoefte. Aan de hand van drie verschillende vormen staartvinnen zijn prototypes gemaakt die aan een speciale verticaal op en neer bewegend apparaat boven de kweekbak bevestigd kunnen worden. De experimenten concluderen dat de onderwater vin gebaseerd op de staartvin van de grijze walvis het meest efficiënt een geschikte stroming kan maken. Deze oscillerende vin wordt nu gebruikt om met minimale elektriciteitsbehoefte een rustige voortstuwende stroming te maken in de kweekbakken bij BlueLinked, waarin alle kleine organismen kunnen overleven. Geïnspireerd door de natuur en gerealiseerd door de natuurkunde is het probleem opgelost en wordt er bijgedragen aan duurzame viskweek.

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Introduction

The global human population is dramatically rising and so is the demand for food. In particular the production of useful proteins has become increasingly important. Fish meat has the potential to be the highest-quality animal protein provider for the human diet with the smallest footprint. Although, great steps can still be made in the aquacultural breeding of fish spawn to adults.

The protein conversion ratio of edible fish versus meat like beef, chicken or pork is far apart. Especially the enormous amount of water that is needed to produce meat makes fish the low-carbon animal protein option. (Guzmán-Luna et al., 2021; Welch et al., 2010). Several life cycle analysis (LCA's) proved fish having the smallest impact of animal proteins for human food production (Lane et al., 2014). However, capturing more marine fish than the ecosystem can grow disrupts the oceanic ecosystems and destroys the balance of the natural earth with accelerating consequences of climate change and biodiversity loss.

The transition from wild fishing to farming has started. Sea cages, nets or ponds with intensive monocultures are applied resulting in negative environmental impacts with concerns about animal welfare. Large-scale pollution and eutrophication of the coastal areas do not seem to compete with profitability of the mass production. Fishmeal, fish oil and soy meal are used as main resources for the diets of farmed fish and antibiotics and nutritional additives are added. Hatcheries specifically are low performing and use inappropriate food supplies (European Climate, Infrastructure and Environment Executive Agency et al., 2021; Neori et al., 2007).

The survival rate during the first stages of fish larvae is suffering under mass mortality due to unnatural circumstances. The ratio of the size of the growing fish larvae and their food is out of balance, has a lack of live feed which is not constantly available inducing high rates of cannibalism. The light conditions are unnatural which often damages the developing retinal tissues, causing bad eyesight and hold back from learning to hunt or detect food. An omnipresent stressor for culturing fish larvae is the chaotic and harsh water flow, used to keep the big volumes of water mixed and oxidated. When a fish farm can grow up around 15-20% of the initial fish larvae to fish fry (the stage after juveniles, when they can go to outgrow systems), and thus losing a vast majority in the early stages, it is doing a great job. In general, surviving past day 16 seems to be crucial (BlueLinked et al., 2022; Fiksen et al., 2002; Hu et al., 2018; Morgan, 1995; Muniesa et al., 2022; Welch et al., 2010).

Currently, a few alternatives for the traditional marine aquaculture are rising. For example, recirculating aquaculture systems (RAS) and integrated multi-trophic aquaculture (IMTA), where waste streams are minimized. At the same time, the energy and space requirements are high resulting in a big carbon footprint. These new forms of culturing marine fish seem to be less bad, but do not reach the goals of sustainability that humanity has to achieve (European Climate, Infrastructure and Environment Executive Agency et al., 2021; Knowler et al., 2020; Neori et al., 2007). Concluding, the urgency for a global sustainable revolution in marine aquaculture remains (van der Meer, 2020).

BlueLinked

BlueLinked, in cooperation with the Oceans at Work Foundation, is an innovative start-up that wants to contribute to a healthy marine environment. Since 2011, it worked on the development of something completely new: a hatchery tank called TinyOcean for the breeding of marine fish species. It is a closed system on land which is low in energy use, animal friendly, circular without waste streams, free of medicines and matching with nature. At BlueLinked, the vision is to eat seafood and restore the oceans at the same time. "*One fish on your plate and one fish in the sea*" should be possible for a big range of marine species, expecting to start with oysters, turbot and cod. In a climatized room, the survival rate of the fish larvae will be at least 80-90%, which is more than 60% higher than current aquaculture (BlueLinked et al., 2022; Oceans at Work Foundation et al., 2022). The hatchery tanks of BlueLinked focus on an innovative approach with trophic diversification. Figure 1 shows the core organisms in the TinyOcean.

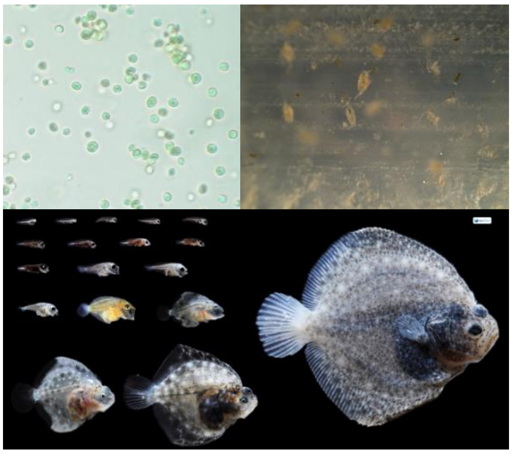

Figure 1: The three main links in the breeding system of BlueLinked (pictures not to scale). Top left = phytoplankton (Bin Latheef, 2012), top right = zooplankton (Tomson, BlueLinked, 2022), bottom = fish larvae stages; turbot in this picture (*Scophthalmus maximus*) (Laterveer, BlueLinked, 2014).

To reach the high survival rate, the marine fish larvae are kept with living prey. Starting with the unicellular algae, the phytoplankton, which serve as primary producers since they can photosynthesise. The phytoplankton serves as food for the zooplankton: rotifers and copepods. Subsequently the fish larvae can consume the zooplankton. Plankton in general refers to organisms that float in the water and are usually not able to swim against a current. Zooplankton species transform through several stages of life (copepod example: eggs, nauplii, copepodites, adult) matching multiple sizes of living prey for the developing fish larvae to eat up in the food chain. This resembles the natural food availability as in a real ocean. Since the larvae have always the right size of food around them, cannibalism is reduced to a minimum. The fish breeding in the TinyOcean consist of consecutive phases of predominant organisms in the food chain. After one to three months the fish fry is ready to harvest, and the system can regenerate the balance by itself and will be ready for a new load of marine fish spawn (which is about 25.000 larvae at a time).The fish output went through a natural growth cycle with adequate nutrition uptake, show natural behaviour and will become healthy fish adults when transferred to the follow up outgrow systems. Because of the development of natural behaviour in the mimicked open ocean, the cultured fish is able to thrive in the real sea and can sustain and restore wild populations (BlueLinked et al., 2022; Borges et al., 2005; Dhanker et al., 2012).

The detritus that arises in the TinyOcean ends up on a gravelly/sandy bottom which serves as a living purifying seabed (Figure 2). Aerobic and anaerobic microbial communities inside this part of the TinyOcean decompose the organic waste products like phosphate and nitrogen and create nutrients for the algae, closing the cycle. This makes the system ecologically balanced and makes mechanical filters redundant. As a result, the water is fully circular and never needs a change, except for replacing the evaporated water. The system stays clean and full of life, making it independent of saltwater intake and is not coast bound (BlueLinked et al., 2022; Lønborg & Søndergaard, 2009). Marine fish production would be locally available without lots of transport costs and emissions.

TinyOcean

Natural water movement is necessary to keep the water well mixed and full of life, and to ensure that the waste products flow to where the sandy bottom is. A slow and steady flow would be best suitable for the system. Pumps (impellers) and other mechanical propellors are unusable, because of the huge creation of turbulent motion in the water. The zooplankton and fish larvae are too fragile and will not survive turbulence. Copepods and rotifers will lose their legs and antennae and will decease or lose the physical ability to hold other individuals in order to reproduce. Fish larvae are very vulnerable as well and will get battered fins and eventually die (BlueLinked et al., 2022; MacKenzie & Kiørboe, 2000).

In short, the challenge is to create a water flow which mixes the water but leaves the most fledging marine life intact. Figure 2 displays the design of the TinyOcean.

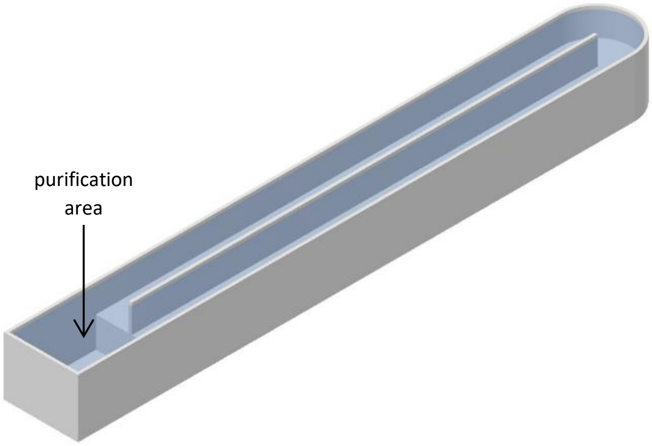

Figure 2: Schematic 3D overview of the outlines of a TinyOcean (Nico Leeuwestein and Floris de Veld, 2022). Note: a not shown septum rounds the angular end symmetrically to the other end of the basin.

The long wall in the middle of the TinyOcean creates a circular flume of almost twenty metres. This flume is designed to navigate all the detritus suspended in the water to the side where the purifying seabed is located (the angular end). Figure 3 shows the bottom of the tank, especially designed from this point of view.

Figure 3: Picture from inside an empty TinyOcean, taken from the purification part (front region), with at the left side a deeper water column than the shallower right side. The red arrow indicates the designed flow direction. The flume is slowly descending to the middle wall as well, extra stimulating the sediment to end up on the seabed.

The flume bottom descends slowly starting after the seabed (right side Figure 3) all the way back to the seabed (left side Figure 3). Because of the flow direction and the help of gravity, the natural detritus ends up in this "living soil".

The descending bottom is next to the purification area creating a "shallow" and "deep" water column, in Figure 3 on the right and left side respectively. There is an elevation of the bottom directly after the seabed (purification area). Since the TinyOcean is a closed system, this smaller passage causes the same water volume to increase in velocity at this point because of Bernoulli's principle which states that acceleration of gravity times depth plus ½ times the velocity-squared should be constant, and water is a medium that cannot be compressed like air can do (Faulkner & Ytreberg, 2011). That is why in theory, the shallow water column will have a slightly faster flow rate compared to the deep water column.

Biomimicry

Perhaps the discipline of biomimicry can help in the challenge of creating a water flow which mixes the water but leaves the most fledging marine life intact. As reported by Dayna Baumeister and Janine Benyus, the two driving forces behind the biomimicry research field, innovative biomimetic solutions can be created for all the challenges humans are facing by integrating biology into design (Baumeister & Benyus, 2011). When nature is used as a model, mentor and measure, the bio-inspired innovations are defined as more efficient and more sustainable in terms of climate impact than the custom mechanical solutions (Dicks, 2016).

"Life creates conditions conducive to life", a quote from Benyus, explains the theory behind biomimicry. Nature does not maximize, like humans tend to do, but optimize in such a way that many future generations can still live the same life. Organisms have figured out over hundreds of millions of years what the best strategy is for living the most efficient way in their own context. During the still ongoing evolution of life, in every context only the most optimized designs are able to thrive (Baumeister & Benyus, 2011).

Although, there are some reasons to be sceptical about the potential of biomimicry. The solutions of nature are designed in a context and cover multiple functions. Optimizing a certain characteristic for the context it is functioning in can be to the detriment of the optimization of another characteristic with a different function (Fisch, 2017). For example, sponges can create an internal flow with their pores and canals so that they can filter-feed out of the circulated water. However, the structure that pumps water through the animal also serves as a tide current breaker and contains specialized cells for processes like digestion and excretion and can house symbionts (Thacker et al., 2014). The design of the sponge is optimized for a complex context and is multifunctional. To thrive as an organism the balance of adaptations is optimized instead of every adaptation on its own. For the biomimicry approach, it is important to not just copy how nature looks but be inspired by nature and mimic the functioning (Baumeister & Benyus, 2011).

Another side note from biomimicry is the lack of critical reflection and just assuming that nature's genius is the top of efficiency. The field is rising since 1997 but still seems philosophically underdeveloped (Mathews, 2011). It only brings together scientists with a practical focus and the outcomes are more important than the understanding. Nevertheless, biomimetic applications that are proven to be effective are highly, and increasingly, popular in today's society (Dicks, 2016).

Using this information, it would be interesting to discover the possible solutions nature has for the challenge of creating a non-turbulent water flow in the TinyOceans of BlueLinked.

After comparing multiple ways of generating a flow, there has been looked to the option of using a drive belt to create flow, which started from an inspiration by organisms that use a similar phenomenon for their locomotion. The drive belt with scopes would hang above the water surface, with the bottom scopes going through the water column. However, this belt-driven stationary flow will be high in energy consumption because of the battle with the drag forces when lifting the scoops out of the water (Bech et al., 1995; Bouma et al., 2005). Furthermore, this method would be highly intrusive in the flume of the TinyOcean, risking damage on the organisms.

Next to that, recently a method is developed to cultivate salmon in pools below sea level with a laminar flow by using the different water layers of the sea (Hatchery Feed & Management, 2021). But, despite the low energy use, this is basically another variant of nature intrusive aquaculture which is coast bound. Another solution for the challenge in the TinyOcean is still needed.

Inspired by whale species

Tail fins (symmetrical caudal flippers, known as flukes) of whale species (called cetaceans; whales, dolphins, porpoises) are designed to move big bodies of water. More than the vertical fins of fish species, these fins are mainly focused on achieving slow and steady motion through the water in one direction (thunniform style), instead of constantly making short accelerations and turns (Fish, 1996; Fish & Lauder, 2017; Sfakiotakis et al., 1999). So, the ancient adaptation of whales to the aquatic life will possibly lead to an inspiration for creating the desired flow in the TinyOceans.

In many ways, swimming is nothing more than flying in much denser fluid. Aquatic life has mastered their underwater flight for countless generations. The results are complex and elegant ways of creating propulsion. Caudal fins found in nature are very diverse but have propulsion as a common primary function. To do so, all the fins have a hydrofoil shape in common. These streamlined wing-like lunar shapes have cross-sections with the outline of a droplet. The rounded leading edge (close to the tail) minimizes drag when moving through a fluid by reducing the pressure gradient and making lift force possible. Instead of paddling and generating a drag-based propulsion, this lift-based locomotion is based on the undulation of the body (Fish, 1996). The different morphological tail flukes cover a vast range of flow parameters. The properties depend among others on aquatic behaviour, focussing on aspects as low in weight, low in drag and high in thrust with minimum energy input (Dagenais & Aegerter, 2020; Woodward et al., 2006). The relative size of the surface area compared to the span width can be contrasted with the aspect ratio, a number equal to the span-squared divided by the surface area (Pavlov et al., 2021). The higher the aspect ratio, the narrower the fin.

With this information, the caudal flukes of three species of cetaceans are selected to continue the experiments of this research with (Figure 4).

Eschrichtius robustus, known as the gray whale, has the longest migration of any mammal and is characterized by a sustained and steady motion (Garrison & Ellis, 2016; Swartz, 2018). Gray whales do not have to hunt actively since they are baleen filter feeders and are even specialized on bottom feeding (Woodward et al., 2006). Bottoms do not swim away, so the main function of this caudal fin is efficient low-speed manoeuvring. With an aspect ratio of 3.76, their caudal flukes have a relatively large surface area and thus will be called "large fin" from now on.

Balaenoptera acutorostrata, the dwarf minke whale, has long migrations and filter feeds as well but is significantly hunted by killer whales. As a consequence of evolution, this species developed to be agile as well (Perrin et al., 2018). The surface area of the fin is relatively small with an aspect ratio of 5.90, so this fin will be called "small fin".

Tursiops trancatus, the common bottlenose dolphin, with an aspect ratio of 4.30 it will represent the "medium fin" in this study regardless of the smallest body length of the three chosen species. This cetacean species is a fast swimmer which can accelerate quickly and is a very agile hunter (Pavlov et al., 2021). With these three fins, a broad range of fin surface areas is covered as well as different functions and contexts.

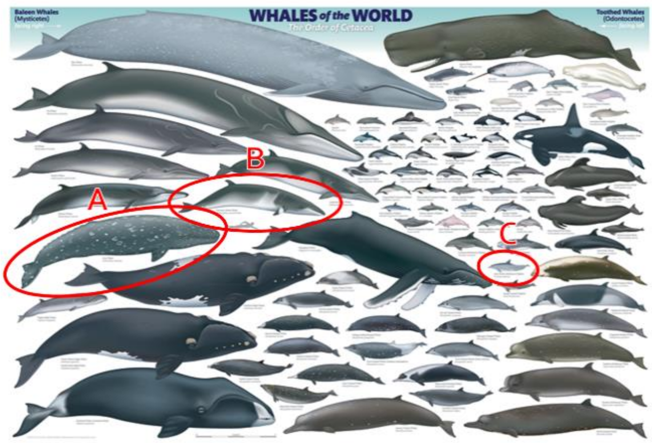

Figure 4: The whale species of the world. A = *Eschrichtius robustus* or gray whale, B = *Balaenoptera acutorostrata* or dwarf minke whale and C = *Tursiops trancatus* or common bottlenose dolphin (The Whale Museum, 2020).

However, just like the previous discussed sponge example, the tail fins of cetaceans are evolved to be multifunctional. The flukes are functioning for thrust production, stability and control during the swimming movements, creating the right buoyancy, thermoregulation and in some species, it even functions as sexual distinctiveness, for recognizing the shapes and behaviour of relatives and to form bubble rings at the water surface to play and hunt (Pace, 2000; Pavlov et al., 2021; Ralls & Mesnick, 2009). The shape of the flukes is just one of the different demands of a certain body part of these aquatic creatures.

Fluid dynamics of a foil

At the start of this project, an online meeting with Prof. Dr. Frank Fish from West Chester University of Pennsylvania, USA, was of special value (for transcript, see Appendix 1). His research is focused on the energetics and hydrodynamics of aquatic locomotion with biomimetic applications. He is specialized on biomechanics of the propulsive systems for swimming by aquatic animals. Experimenting with monofins (fused flippers to attach on the feet of humans for swimming) designed for free-divers, the properties of the caudal fins seem to outperform the other monofin designs (Appendix 1). So, Fish suggested using the foil dynamics of cetacean flukes (Figure 5).

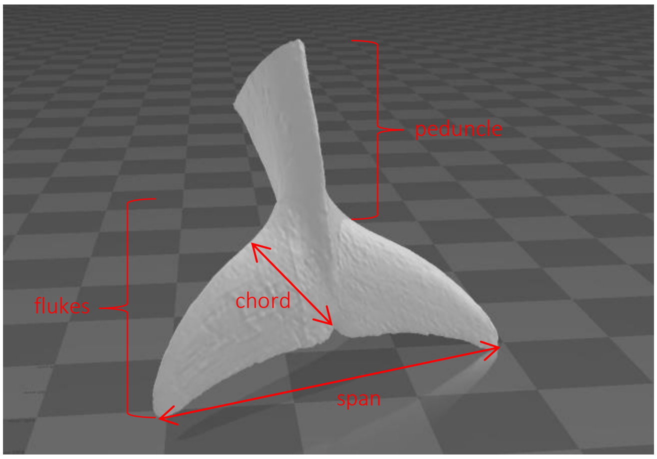

Figure 5: Harbour porpoise tail fin including the peduncle in a 3D model adapted from Prof. Dr. Frank Fish.

The distance from the trailing edge (the end of the fluke) to the leading edge (the start of the fluke, close to the tail) of the hydrofoil is considered as the chord length, see Figure 5. Just like in aerodynamics, the bigger the chord of a hydrofoil, the higher the lift generation and lift force distribution (Ward-Smith, 1984). That means that the lift force generation becomes smaller towards the wingtips with highest value in the middle of the fin. This translates spanwise flexibility into a characteristic that enhances the propulsive motion, to a certain extent. This depends on the angle of the foil and moves up and down in a cycle cooperating with drag and gravity on the foil. Also, it turns out that the pattern of lift distribution towards a wing tip causes a reduction in vortex creation (Pavlov et al., 2021).

Fish pointed out the importance of the peduncle to create the undulation movement that turns out to be efficient for big swimming mammals like whales. Next to that, chord-wise flexibility decreases the magnitude of the vortices attached to the surface of a hydrofoil. The vortices appear earlier during the oscillating movement and shed off faster (Xu et al., 2019). Fish also recommended to make the fin flexible both chord-wise as span-wise, so that the pressure can be distributed along the foil surface (Fish et al., 2018) (Figure 6).

Foils create both lift and propulsion and perform outstanding in vorticity control. Vortices are only allowed when they are structured, so they do not interfere with each other and fade out in a Kármán vortex street (Schnipper et al., 2009).

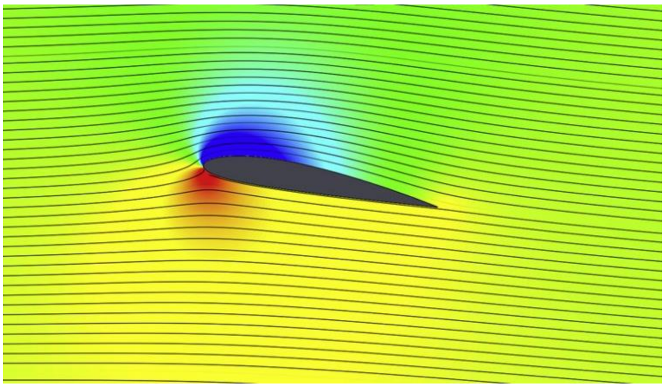

Figure 6: Pressure distribution around a foil (red to blue scale, red is high pressure and blue is low pressure). The black lines are flow lines. The flow velocity is parallel to the nearest flow line and in magnitude inversely proportional to the distance to the next flow lines. With Bernoulli's law (pressure + ½velocity^2 is constant) this shows why the pressure is higher at the bottom side where the flow lines are diverged further from each other, versus the top side where they are squeezed together, leading to a lift force (Hetyei et al., 2020).

As used in the design of airplane wings, these oscillating foil shapes have the ability to generate high lift forces. The thrust is high because of the lift force. As a consequence of the rounded upper surface in the cross-sectional geometry, the velocity on the surface of the foil is increased in contrast to the bottom of the foil. This results in a high-pressure region at the bottom of the foil which causes the foil to get lifted. This is known as Bernoulli's principle. Once the angle of the swept foil is further increased, and the boundary layer adhered to the surface can no longer follow the profile, the lift diminishes and drag and gravity take over and pull the foil downwards again (Faulkner & Ytreberg, 2011; Fish & Lauder, 2006; Ward-Smith, 1984; Xiong et al., 2021).

Turbulent vs laminar

Schetz and Fuhs have described turbulence as follows in their book in 1999: '*turbulence is defined as an eddy-like state of fluid motion where the inertial-vortex forces are larger than any other forces that tend to damp them out*' (Schetz & Fuhs, 1999). Most flows around are turbulent instead of laminar (Figure 7). In order to avoid turbulent water in the TinyOceans, it is important to prevent the vortices that are formed to interfere with each other.

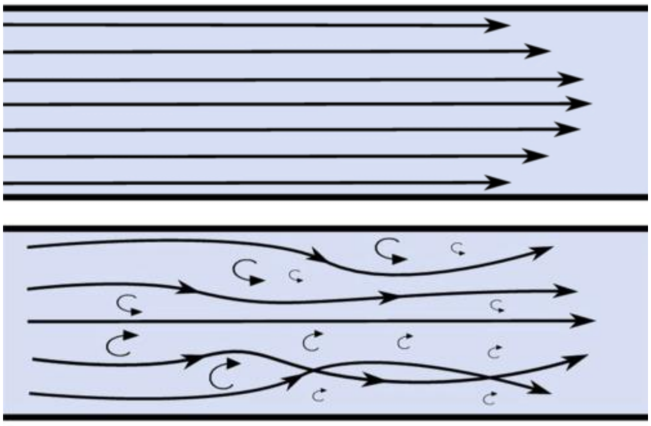

Figure 7: Laminar (top) vs turbulent (bottom) flow (Ameri, 2019).

Big vortices have little vortices around that feed on the additional velocity. The smaller the vortex, the lower this additional velocity and the closer to viscosity. (Ward-Smith, 1984). A vortex that is shed off the oscillating fin and subsequently slowly damps out without amplifying other vortices, in theory could not be harmful to the plankton species and fish larvae (Schnipper et al., 2009).

The fluid parameters influencing the motion are the flow velocity U, characteristic length L (in this context the chord length), fluid density ρ and the fluid viscosity μ. To determine turbulence, these parameters can be combined into the Reynolds number:

$$\mathrm{Re} = \frac{\rho U L}{\mu} = \frac{UL}{v}$$

Where v equals μ/ρ and represents the kinematic viscosity of the fluid. Note that Re has a dimensionless value. Reynolds numbers <2000 are interpreted as laminar flows and means that the viscous forces predominate. When Reynolds numbers pass 4000 the flow environments starts to become turbulent, which means predomination of inertial forces. Everything in between is considered intermediate and expresses flow-transition (Schetz & Fuhs, 1999; Ward-Smith, 1984). However, aquatic animals like cetaceans usually operate at high Reynolds numbers ranged 10^5 - 10^8. Their swim speed and the velocity of the water are not made to generate low Reynolds numbers. Although the water around cetaceans is turbulent, the streamlined and hydrodynamic shapes are effectively separating the layers of water to glide efficiently with minimum drag (Fish et al., 2008; Kunze, 2019; Soboyejo, Daniel, et al., 2020).

Another important dimensionless parameter is the Strouhal number. In fluid kinematics, this number describes the mechanism of an oscillating flow (propulsion dependence on oscillation) as follows:

$$\mathrm{St} = \frac{fA}{U}$$

Where f is the frequency of the strokes (cycles per second, in Hertz), A the amplitude and U the flow velocity. When St has a value between 0.2 and 0.4, the propulsive efficiency is high and indicate the absence of crossing layers in the fluid. It turns out that cetaceans flap their tails with St values in this range. Greater Strouhal numbers lead to slower vortex shedding and thus bigger vortices. Dimensionless numbers are a good tool to quantify and compare dynamic systems (Anderson et al., 1998; Rohr et al., 1998; Schnipper et al., 2009; Taylor et al., 2003).

In context of an oscillating underwater fin, maxima in thrust (or generated flow) are found when the oscillation frequency matches one of the natural frequencies. The natural frequency is determined by material properties and dimensions of the foil. Flapping efficiency (enhanced by flexibility to a certain extent) is synonymous with increasing propulsive power of a free-moving fin. When the wing is fixed at one place, as in the TinyOcean, it means generation of maximum flow (Michelin & Llewellyn Smith, 2009).

In short, for the context of the TinyOcean, the goal of the oscillating underwater fin should be to generate a non-turbulent flow with Re <4000 and to oscillate efficiently with 0.2< St <0.4 as important values. The small inevitable vortices that still occur in this situation should not interfere.

Aims

Marine aquaculture is a complex research field, but in the context of the discussed innovative approach from BlueLinked the following research question is investigated:

How to generate a plankton and fish larvae saving water movement in BlueLinked's TinyOcean?

Taking the theory of the Introduction of this thesis into account, the follow-up question is:

Will the biomimetic design of an oscillating underwater fin beat the custom mechanical way of creating a water flow in the context of BlueLinked's TinyOcean?

The expectation will be to confirm that the bio-inspired underwater fin turns out to be more efficient and best suitable for the context it is designed for, generating a non-turbulent flow in a TinyOcean. However, maximum thrust is not the only function of natural flukes so the experiments will show how big the trade-off was during many years of adaptation to multiple challenges in the aquatic life.

Experimental research

For the timeline of the experimental research of this project, the logbook in Appendix 3 can be consulted. Below are the methods of this project described. Appendix 2 can be consulted to have access to all the supporting imagery.

Creating prototypes

The natural aspect ratios of the shapes of the flukes of the chosen cetacean species are preserved in 2D 4mm thick rubber (styrene-butadiene rubber) prototypes of all 54 cm in span to fit perfectly in the flume (561 mm width) of the TinyOcean (Figure 8) (Pavlov et al., 2021; Woodward et al., 2006).

Figure 8: The first prototypes, all 54 cm width. Surface area of large fin = 775.53 cm^2 with aspect ratio 3.76 and chord 17.5 cm, medium fin = 678.14 cm^2 with aspect ratio 4.30 and chord 16.0 cm, small fin = 494.24 cm^2 with aspect ratio 5.90 and chord 12.5 cm.

Determining the stiffness

With the shape and size known, the next question was how flexible they must be to not only look like nature, but also work like nature. In this first experiment, the stiffness, the force required for lifting a third of the span (18 cm) was measured (Figure 9). This stiffness was the first property obtained to compare the fins with each other.

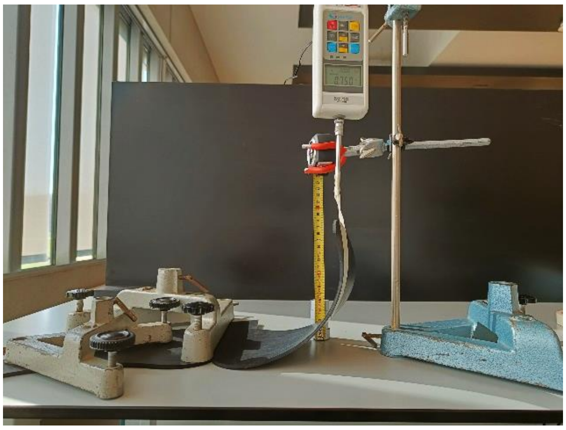

Figure 9: The setup to determine the stiffness of the prototype fins using a digital force meter (Newton) and lifting a tip to 1/3rd span.

The results ranged around 1 Newton, with a correlation between a bigger chord and a higher stiffness. Next, the behaviour underwater would be interesting. Observations in a swimming pool were conducted by moving the fins by hand (Figure 10) (Appendix 2 for the videos).

Figure 10: Discovering the underwater behaviour of the first prototypes in a swimming pool. The size of a white background tile is 24.0 cm high and 11.5 cm wide.

It turned out that gravity is too strong, and the fluke tips started to hang down and did not behave in a natural way. It is expected that the prototypes should be stiffer to match the properties of real flukes. Questioning the material to use to make the prototypes more rigid, cetaceans flukes are built with a big core of collagen fibers strongly connected to the caudal vertebrae. These fibers are arranged in horizontal, vertical and oblique arrays which get less dense towards the fluke tips (Fish, 1998; Fish & Lauder, 2017).

Optimization based on real harbour porpoises

In collaboration with the Pathology department from the Veterinary Pathological Diagnostic Center (VPDC) of the Faculty of Veterinary Medicine of Utrecht University, a dissection of two freshly stranded harbour porpoises (generally, the only available cetaceans in The Netherlands) was performed in order to understand the shape and function of the real natural design (Figure 11).

Figure 11: Two real harbour porpoise tail fins, sawn off the body, but including the peduncles. Left: adult, right: young adult.

Here, the same stiffness experiment was performed to use the results for improving the prototypes (Figure 12). The results were around 2 Newton, meaning twice as stiff as the first prototypes (due to the scope of this project, a simple value like this will be enough to make prototypes that function like real fins and will not go into more detail at this part, however, the obtained data can be requested from the author).

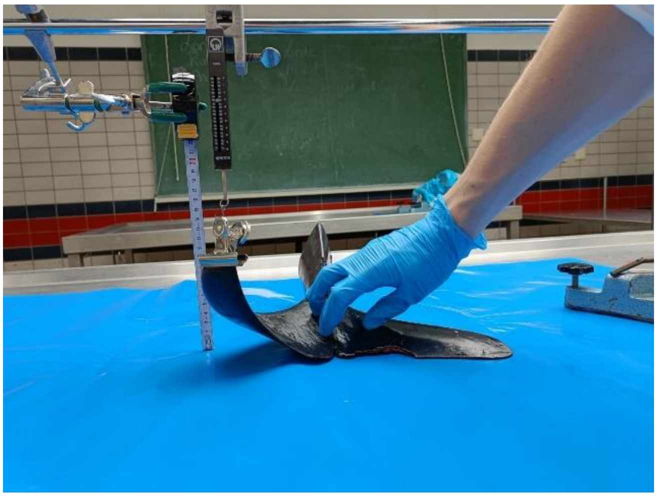

Figure 12: The setup of the stiffness experiment with a real harbour porpoise fluke, using a force meter (Newton).

According to the harbour porpoise findings, the first prototypes were reinforced with two layers of strong but flexible polyethylene (0.8 mm thick) in a certain shape inspired by how the real fins were feeling (Figure 13). Repeated stiffness experiments eventually resulted in a stiffness value similar to that of the real flukes. New successful videos were made in the swimming pool, see Appendix 2.

Figure 13: The reinforced prototypes with two specifically shaped layers of 0.8 mm polyethylene (light grey colour in this picture) added to each fin, making each fin 5.6 mm thick.

Remarkably, the weight per surface area of the fins is linear related (Figure 14). So, a bigger fin means a comparatively heavier fin, and this is also in line with the ratios of the harbour porpoise flukes.

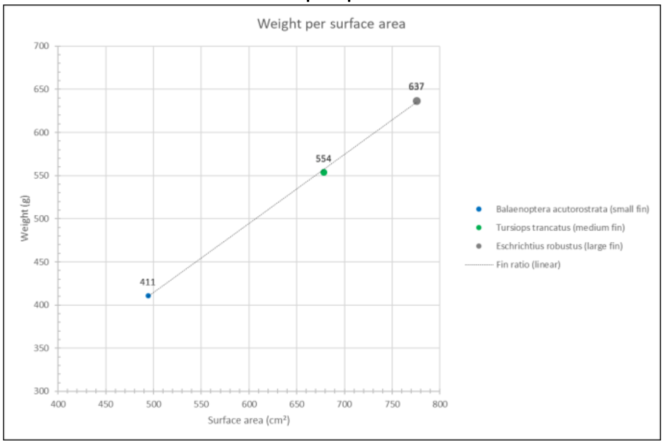

Figure 14: The weight per surface area of the three fin prototypes, showing a linear correlation.

In order to compare the bio-inspired properties, some default shelves were made, a stiff and a flexible version. The shelves are 54x12 cm^2, the average surface area of the three fins combined. The stiff shelf is made out of compressed hardboard and the flexible shelf is made out of the same rubber and polyethylene (in ratio) as the fins, with the same thickness as the fins (5.6 mm). With these shelves, the effect of both shape and stiffness can be determined and will show if the bio-inspired properties really matter.

The oscillating regulator

For this project, a regulator that oscillates the fins in the water column just like they do when attached to the body of a whale is made. This driving machine including the built-in torque motor is called the oscillating regulator (Figure 15). It can be placed on top of the flume so that the fin is placed in the water from above.

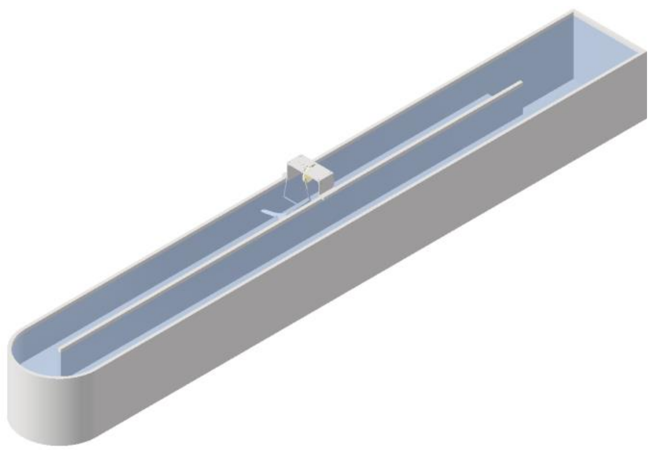

Figure 15: Schematic overview of the outlines of a TinyOcean, including the oscillating regulator with fin located in the centre (Floris de Veld, 2022).

During the dissection of the harbour porpoises, the peduncle was investigated as well. This brought a clarifying insight. There are no bony supports in the fluke blades, but small vertebrae are present in the centre of the tail fin (Figure 16). In contrast to fish species, which are not derived from terrestrial animals in the evolution of aquatic life (Fish & Lauder, 2006). For more (slightly bloody) imagery of the dissection of the harbour porpoises, Appendix 2 can be consulted.

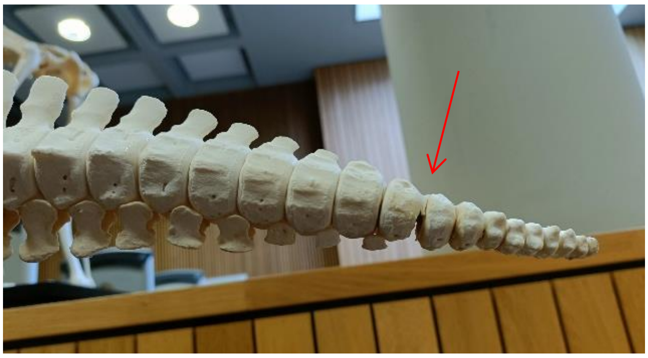

Figure 16: Skeleton of a harbour porpoise, zoomed in on the last part of the tail. The red arrow is pointing to the joint in the last part of the spine, called the peduncle, which is just a little up the tail of where the fin comes into the body. The vertebrae are such that they allow greater flexibility there.

Remarkably, the large intervertebral spacing inside the peduncle functions as a hinge joint at the base of the flukes (Fish, 1998). This determines the angle of attack of the flapping motion and with this the vortex shedding (Fish et al., 2018) (Figure 17).

Figure 17: Harbour porpoise swimming undulation (screenshot of a video from WeDive TV, 2018). The red arrow indicates the joint that allows the fin to flap including a certain flexion in the flukes itself.

The new insights, improved prototypes and ready to use oscillating regulator will put the efficiency of the prototypes to the test. At this point, mimicking a functional peduncle has been postponed.

Methods for measuring the flow

To determine the efficiency of the prototypes, there are two main parameters to quantify. First, the energy that the oscillating regulator is using with different prototypes attached is important to be able to compare them. This was simply done by adding an electric current meter in the circuit of the oscillating regulator. With the power adapter's known voltage of 24 volt, the power consumption in Watt could be calculated.

Second, the generated flow velocity of the water in the flume gives the information to set the fins apart regarding efficiency. This experimental research is looking for the prototype that can produce the highest flow rate while using the least energy.

Ultrasonic Flow Meter

The first method executed to quantify the velocity of the water was using an 'EMCO Sono-Trak^{TM} - transit time ultrasonic flowmeter ST-30', based on the differential transit time method using ultrasound.

This device is coming with clamps to attach two transducers at the outside of a pipe. The transducers are both transmitting and receiving high frequency ultrasonic waves through the fluid inside the pipe. These signals are generated with crystals applying a voltage, conversely, the crystals create a voltage when an ultrasonic signal impacts the sensor. With one transducer downstream and the other transducer upstream at the right spacing, there will be a difference in transit time of the impulses when the fluid is flowing. Less time in the direction of flow and more time against the flow. Therefore, the differential transit time measured by the transducers is directly proportional to the mean flow velocity in that cross-section and can be calculated with high accuracy (Engineering Measurements Company, 2000).

When installed with the correct pre-set data, in theory, this method would work in the flume of a TinyOcean. The transducers are water-tight, so one can be installed under water to the middle wall and the other transducer can be installed across on the outside wall. BlueLinked was lucky with owning one of these flow meters. However, after trying to make it work, it had to be concluded that the transducers were too worn and unusable. This method was failed do to material failure.

Electromagnetic Flow Meter

Next, the backup plan was performed. This method is based on the electromagnetic principle. An electrical current can be generated with a magnetic field. Saltwater contains electrolytes which makes it an electrically conductive liquid. In the water column of the TinyOcean are two simple electrodes placed across each other to the side of the wall, due to the lack of an actual electromagnetic flow meter. With the help of a constant vertical magnetic field, the flowing electrolytes will generate a voltage that the electrodes pick up.

Assumed was, that the earth magnetic field would be sufficient to perform this method. The magnetic field applies a force to the charged particles. As a result, the positively and negatively charged particles are separated on the different walls and cause an electrical signal over the electrodes, known as the electromotive force component (EMF). This voltage is directly proportional to the mean flow velocity in that cross-section, based upon Faraday's Law (Leeungculsatien & Lucas, 2013; Lefebvre & Durgin, 1990). As first, with all the different measurements with the different fins, this method seemed to work (Figure 18).

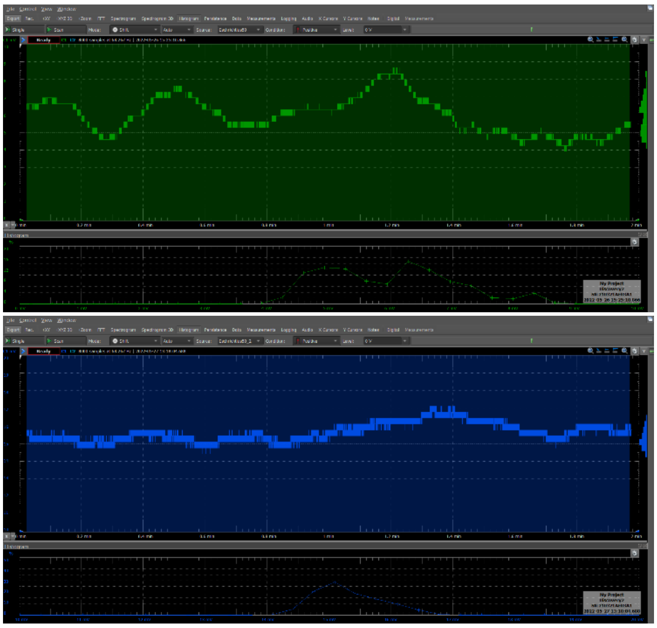

Figure 18: The measured voltage in real time during the oscillating large fin at a certain motor power, visualized by the oscilloscope setting of the software WaveForms. Top: results of the electrodes located one metre after the fin in the deep water column of the TinyOcean, bottom: results of the electrodes located at the directly opposite location in the shallow water column. Both graphs are accompanied with a histogram indicating the confidence of the signal. As expected, the voltage is higher and more stable in the shallow water column in contrast to just a metre after the oscillating fin.

To clear disturbance of possible constant external electromagnetic fields and make a stable measurement, a pulsed direct current can be used by alternately reversing the polarity of the magnets. However, after all, the method could not be validated because of three observations. (1) Adding magnets did not lead to changing voltages. (2) Shutting down the flow in the TinyOcean did not lead to a correct zero measurement. (3) Holding the electrodes in the air did not lead to any voltage, however, stagnant freshwater (reversed osmosis, without any contaminants) on the other hand showed fluctuating voltages that are inexplicable. Altogether, this method failed, but was worth a try (Appendix 2 contains the graphs obtained with the software WaveForms).

Self-constructed Flow Meter

After two failed methods, this project had to develop its own empirical flow meter.

Figure 19 shows the chosen setup of the self-constructed flow meter, based on timing the transport of a floating object. Two stretched fishing lines (indicated with the thin red lines) of a total of two meters are located in the centre of the flume to prevent the floating pvc-tube from sticking to the side and to make sure it stays in the maximum velocity area in the middle of the column (Figure 7 Top). The flow in a flume has a parabolic profile due to viscous effects that require the flow to vanish (velocity = 0) at the side walls. The fluid has zero velocity at the walls and a maximum velocity in the middle, showing a linear variation in between.

The floating pvc-tube is placed in the water column at one side. When it catches its speed in the first half of the track, the time for travelling exactly one metre in the second half of the track is timed. This experiment is conducted at both sides of the TinyOcean.

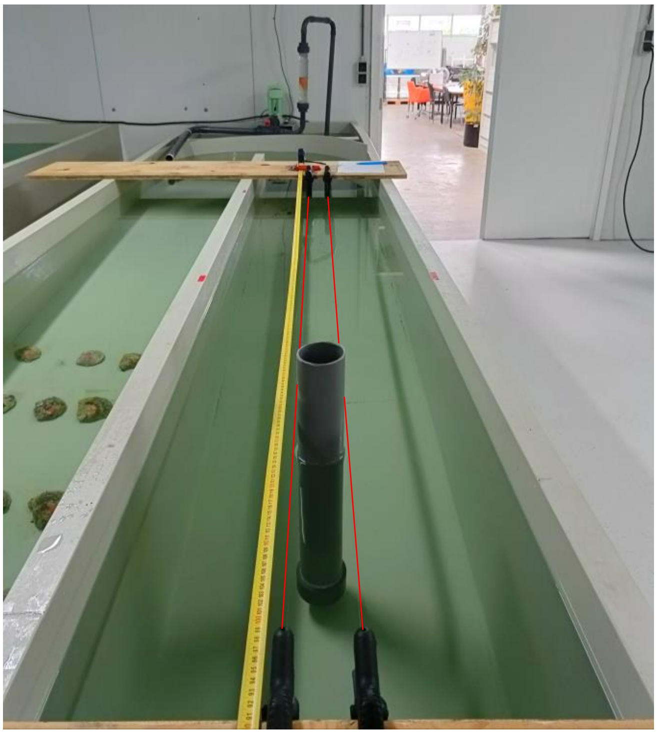

Figure 19: The set-up of the self-constructed flow meter, here in the deep water column. The tauted strings (fishing lines, hard to see) that make a straight track slightly wider than the diameter of the floating pvc-tube are clarified with the red lines. The presence of these tauted strings is important to guide the pvc-tube in a straight line without adding any resistance to it like a wall will do. The yellow tape serves as an accurate measure of distance.

For every situation, the experiment is performed twelve times. By rejecting the two measurements that deviate furthest from the mean, this method ends up with ten measurements in every situation. Graphs are made with the averages.

Results

The next results focus on the question whether the biomimetic design will beat the custom mechanical way of creating flow in the context of the TinyOcean. The self-constructed flow meter measurements will give results to compare different flow velocities (m/min), volumetric flow rates (m^3/min) and energy consumptions (W).

Validation of method

To validate the method of exploring the flow kinematics with the self-constructed flow meter, this experiment needs to be performed with something that generates a known flow rate. A mechanical pump with multiple power modes, using an impeller, was used (Figure 20). With the manual of the pump with the exact indication of the volume transport per power mode, the self-constructed method could be validated.

To be clear, such a mechanical impeller is generating flow in the water starting at the output of the pump, which is very narrow (2.5 cm in this case) and concentrated. The water at this point accelerates so fast that the turbulence will kill all the plankton and fish larvae that are passing this area of ferocity. So, regardless of the output, this pump will not be suitable to settle in the TinyOcean, it is only used for this experiment.

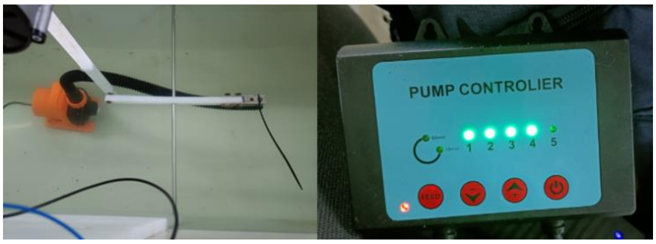

Figure 20: Left: the set-up with the pump, with the hose attached to the end of the (shut-off) oscillating regulator without fin so that the output of the pump is stable and in the middle of the water column. Right: the pump controller with five different power modes (4000, 5600, 6100, 7300 and 8000 L/h).

Flow velocities are calculated from the average time of the pvc-tube measurements. Setting out these results to the pump power modes, makes the graph in Figure 21. The lines increase, which means that the floating pvc-tube is transported faster through the flume of the TinyOcean when turning up the water flow generation of the pump. With this, the method is successfully validated. The differences between shallow and deep water are like expected, while the oscillating regulator was even placed in the deep part. Remarkably, the pvc-tube tends to move sideways when using the pump for the flow generation, visible in the videos (Appendix 2).

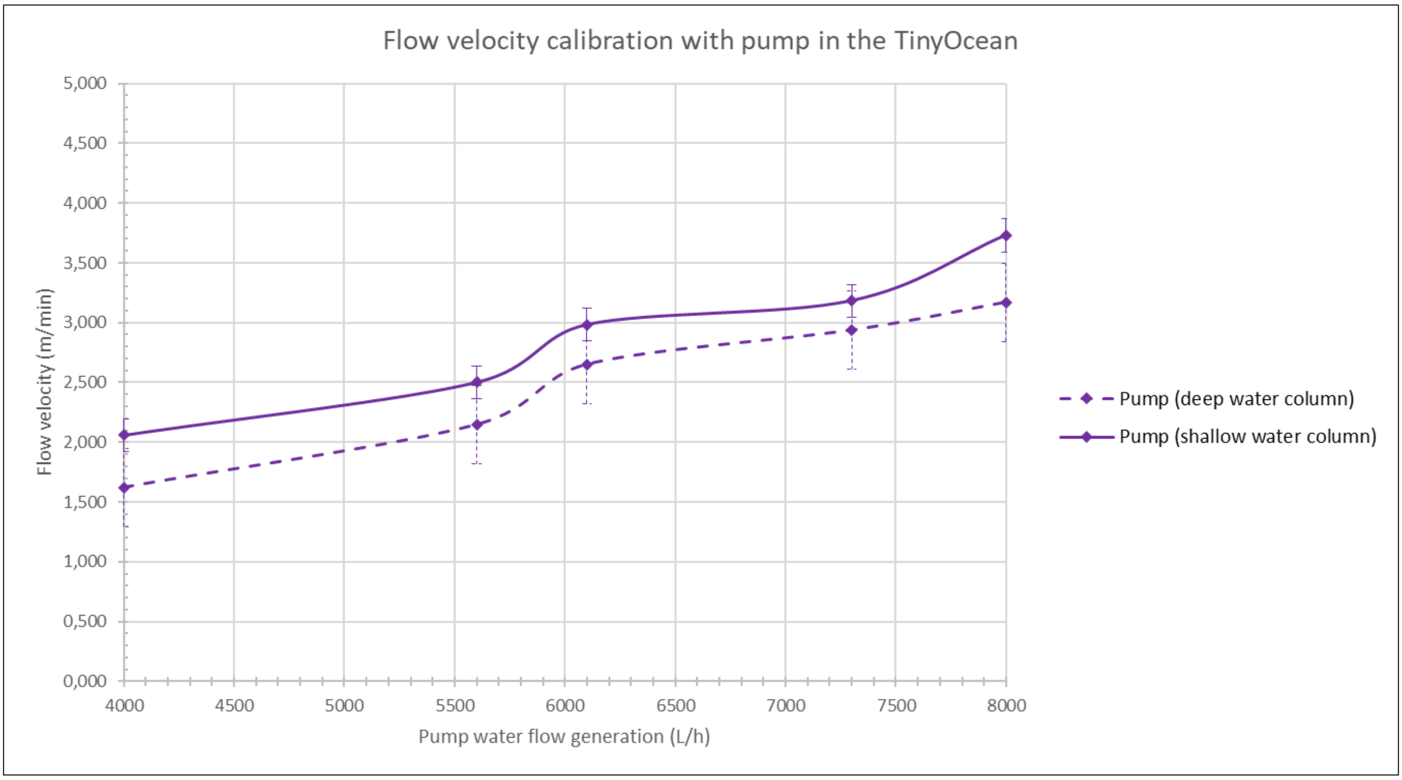

Figure 21: Generated flow velocity using the mechanical pump at different power modes. Dashed line: measurements in the deep water column. Solid line: measurements in the shallow water column (see Figure 3). The lines increase, what indicates that the self-constructed flow meter is working successfully. Besides, it looks like the flow velocity in the shallow water column is consistently higher than in the deep water column. However, the mean standard deviation bars of the measured flow velocity are slightly overlapping, so this conclusion cannot be made with absolute certainty.

This indicates the Strouhal number is beyond the required range, as then the tube starts to shed off alternating vortices. This process induces alternating transverse pressure forces acting on and displacing the tube.

Nevertheless, with this validation, the flow rate can be translated to the whole volume transport of the tank. The volume of the flowing water body is equal to the volume of both the rectangular flumes and both the cylindrical ends of the TinyOcean (Figure 2), thus depending on the average height of the water column. During the experimental phase of this project, the water depth was on average in the middle of the flume width 42.5 cm, which results in a total TinyOcean volume of 4263 litres excluding the purification part behind the half cylinder shaped end ($length\ 7975 \cdot width\ 1122 \cdot average\ height\ 425 + \pi \cdot radius\ 587^2 \cdot average\ height\ 425 = 4263 \cdot 10^6\ mm^3$). Including the purification part, the total amount is approximately 6000 litres.

Flow rate

On to the oscillating regulator with the fins and shelves (Figure 22). Experiments are performed with three motor power percentages (50/75/100%) and not lower than 50% because that was visibly assessed to be too slow to mix the water and move all the detritus towards the purifying end of the TinyOcean. The motor also seemed not powerful enough to raise the shelf or fin through the water. Next to that, there are no results of the stiff shelf at 100 percent of the motor power. In theory, the torque motor should be able to handle it, but the oscillating regulator construction is not strong enough to enable this motion without damage and displacement. With the stiff shelf raising up through the water, apparently there is too much force focussed on a vertical direction instead of pushing to the water in a horizontal way.

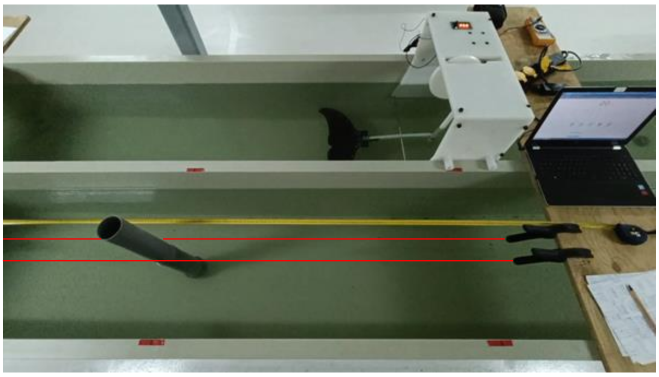

Figure 22: The set-up of the self-constructed flow meter with the oscillating regulator, in the shallow water column. The tauted strings making the track for the floating pvc-tube are clarified with the red lines. The four small red tapes on the walls are indicating the start and end point of the one metre track, according to the yellow tapeline. At the top right, the energy meter that recorded the average motor energy consumption is visible as well.

Because of the flow rate calibration with the pump, the flow velocity, which is a measurement at one point, can be translated to volume transport in the whole system. Analysing the graph showed in Figure 23, it is clear how the different shelves and fins lead to a steady increase in flow with increasing motor power. Multiplying the measured flow velocity with the width and depth of the water column of the experiment, the volumetric flow rate (m^3/min) is expressed. Again, the self-constructed flow meter seems to work properly.

Although it is not yet fully linear. The reason for the flattening at 100% could be the increase in turbulence, that causes the pvc-tube to not move in a straight line forward, which is visible in the videos (Appendix 2). Nevertheless, the lines representing the small fin does continue in a linear way at 100%, in both sides of the TinyOcean. Another observation of the small fin is the almost lack of difference in flow velocity between the two different water column depths. This could be explained by the fact that the small fin kept the biggest amplitude of all at the highest motor power and in this way was still able to generate a constant flow. Or another factor, like the waiting time in between the experiments at different motor powers, plays a role here.

During the flow rate experiments, someone changed the water level in the TinyOcean and was unnoticed at first by a lack of communication. It was thought that water had entered the pvc-tube (perhaps accidentally, overnight) and would therefore be heavier, but it turned out the pvc-tube was touching the bottom because of the bulk of 400 litres water that was pumped out to fill another tank for a different project. In Figure 23, the lines of the stiff shelf and medium fin in the deep water column are dotted and italicized in the legend to indicate that these two experiments were conducted before the unfortunate water loss, and therefore are unfounded. The other experiments are performed afterwards and sequential there was taken care that no more water changes took place in the TinyOcean that was used.

Assessing Figure 23, the large fin shows the highest flow rate for the 50 and 75% motor power measurements. Considering the 100% motor power, the small fin is peaking. But, most important observation, the fins apparently manage to achieve a certain volume transport more easily than the oscillating shelves.

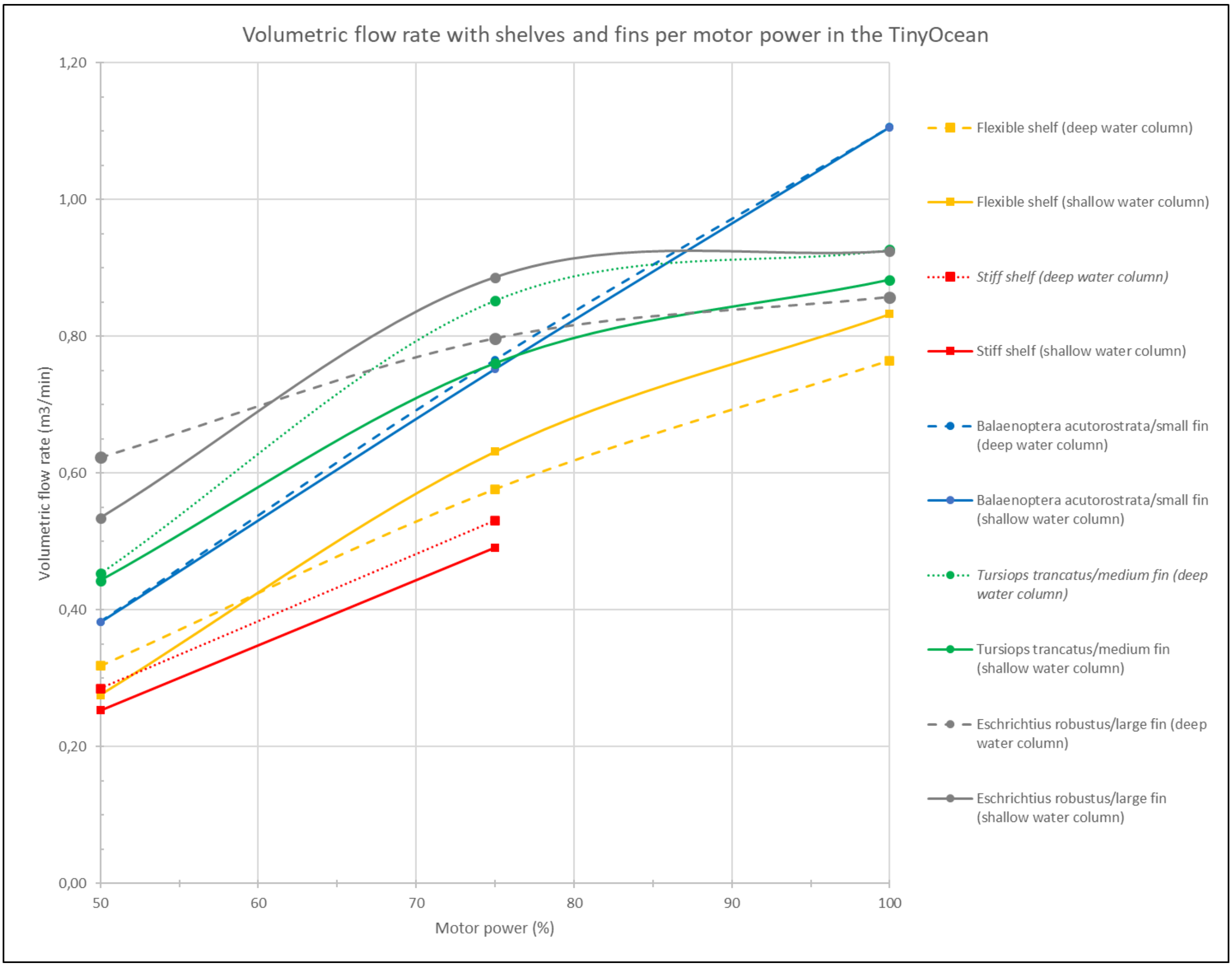

Figure 23: Generated volume transport (volumetric flow rate) per fin or shelf at 50, 75 and 100 percent of the oscillating regulator's motor power. Dashed lines: measurements in the deep water column. Solid lines: measurements in the shallow water column (see Figure 3). Important note: The measurements were obtained over multiple days, starting with the stiff shelf and medium fin in the deep water column (red dotted line and green dotted line respectively, and italicized in the legend). In between these first and the following measurements, there was taken out around 400 L of seawater out of the TinyOcean with the self-constructed flow meter set-up making the deep water column 0.45 m instead of 0.51 m high. This had happened without communication, so all the experiments that followed were unconsciously performed in a lower water column. Although, the weight of the pvc-tube was adjusted down to keep it still hovering just above the bottom. However, since the volumetric flow rate (Q) is calculated as the measured flow velocity (u) times the width (0,561 m) times the height of the water column, the difference in water depth makes the measurements of the stiff shelf and medium fin in the deep water column should not be compared to the rest. The measurements in the shallow water column were all obtained in a water column depth of 0.40 m. The increasing lines confirm the proper working of the self-constructed flow meter.

The flow kinematics can be quantified by determining the Reynolds and Strouhal numbers. Taking the large fin at 50% motor power as example, the flow rate (velocity, U) in the deep water column was 2,467 m/min, equal to 0.041 m/sec. The chord length (L) of the large fin is 0.18 metres. The water in the TinyOcean at the moment of performing the experiment had a salinity of 30.5‰ with a temperature of 17.3°C, resulting in a fluid density of 1026 kg/m^3 and a fluid viscosity of 0.0012 newton-second/m^2 (*Fresh Water and Seawater Properties*, 2011). This makes the kinematic viscosity (υ) of the fluid $1.2 \cdot 10^{-6}$ m^2/sec.

The Reynolds number can be determined, for example:

Large fin at 50% motor power in deep water:

$$\mathrm{Re} = \frac{UL}{\upsilon} = \frac{0.041 \cdot 0.175}{1.2 \cdot 10^{-6}} = 5979$$

Medium fin at 50% motor power in deep water:

$$\mathrm{Re} = \frac{UL}{\upsilon} = \frac{0.026 \cdot 0.160}{1.2 \cdot 10^{-6}} = 3467$$

Small fin at 50% motor power in deep water:

$$\mathrm{Re} = \frac{UL}{\upsilon} = \frac{0.025 \cdot 0.125}{1.2 \cdot 10^{-6}} = 2604$$

Since these Reynolds numbers are higher than 2000, this does not indicate a laminar flow in the direct area of this oscillating fin in these examples at 50% motor power. Actually, the large fin fits in the turbulent regime with the Reynolds number being passed 4000.

In contrast, impellers (installed in mechanical pumps like the one used in this project) add their centrifugal force to the pressure build-up through the narrow output (2.5 cm in case of the pump used for the experiments) leading to radically higher and fluctuating Reynolds numbers (Galletti et al., 2004).

The Reynolds numbers calculated for the prototype fins belong to the adjacent water layers around the oscillating fin. However, viscous forces are expected to predominate further down the flume as the oscillating movements fade away. The calculated Reynolds numbers range around the transition between theoretical laminar and turbulent flow. In the context of a flapping foil, these results are hard to adjust any lower without giving up on the flow velocity. In fact, natural flapping foils are used for pushing off at the water what comes with thin turbulent boundary layers around the foil. (Fish et al., 2008). The combination of a small chord length generating a lower flow velocity gives the small fin the lowest Reynolds numbers in this context. But, to create a higher flow velocity with the small fin, the motor power and frequency must increase, leading to a drastically increase in vorticity.

As a result of a periodic oscillating movement instead of a harsh impeller current, vortices are created in a certain wake formation. For example, at 50% motor power, the stroke frequency (f) of the large fin was 20 up and down beats per minute, equal to 10 cycles per minute. Divided by 60 gives 0.17 Hz, with an amplitude (A) of 0.45 metres. Calculating the Strouhal number will be:

Large fin at 50% motor power in deep water:

$$\mathrm{St} = \frac{fA}{U} = \frac{0.17 \cdot 0.45}{0.041} = 1.9$$

Medium fin at 50% motor power in deep water:

$$\mathrm{St} = \frac{fA}{U} = \frac{0.17 \cdot 0.40}{0.026} = 2.6$$

Small fin at 50% motor power in deep water:

$$\mathrm{St} = \frac{fA}{U} = \frac{0.18 \cdot 0.46}{0.025} = 3.3$$

Again, the medium fin in deep water column had to work through a higher body of water due to a mistake (see important note described under Figure 23), making this equation a bit influenced as well. Nevertheless, the Strouhal results are well aligned.

Comparing to the theory that stated 0.2< St <0.4 should be ideal, these calculated results mean that the oscillation movement dominates the flow around the fin and have a high frequency of vortex shedding. To lower the St numbers, frequency (f) or amplitude (A) must decrease drastically or the flow rate (U) in the centre of the water column (top of the parabolic flow profile) has to increase. Since the amplitude needs to be preferably just slightly smaller than the water column height itself, the logic factor to change would be the oscillating frequency. By turning down the motor power, the frequency is decreasing. However, a very likely co-effect would probably be the decrease of flow velocity, pushing up the Strouhal number again. This shows the need for an external stimulator to increase the velocity of the flow, for example the adding of a second oscillating underwater fin on the opposite side of the TinyOcean.

Note that all the obtained data can be consulted via Appendix 2.

Energy consumption

The flow velocity of the pump measurements ranges from 1.620 - 3.730 m/min. The flow velocity of the fin measurements ranges from 1.515 - 4.926 m/min. Generally, these ranges are matching. The question is whether this also applies to the energy consumption that was needed to generate these flow rates.

First, validate the method for measuring the energy consumption of the oscillating regulator with the shelves and fins attached to it (Figure 24).

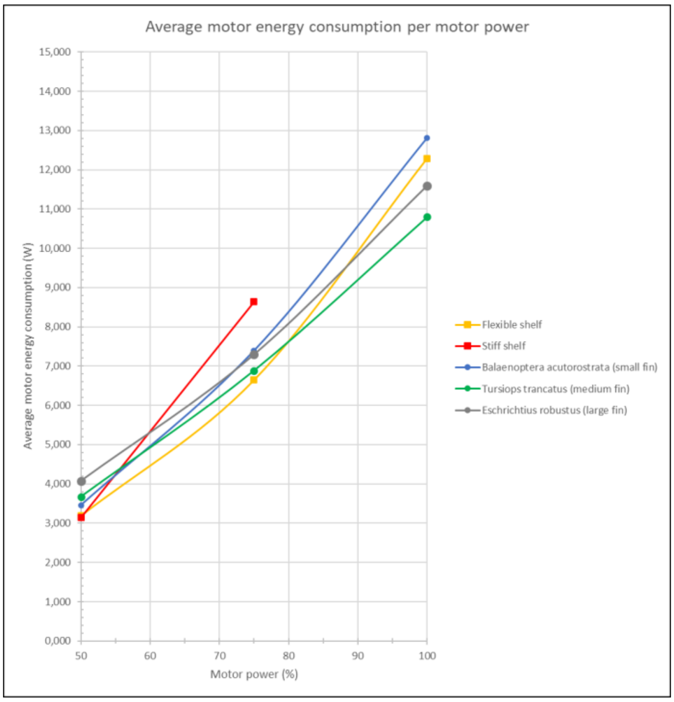

Figure 24: Simple validation of the energy consumption measurements. All the shelves and fins tend to a linear correlation of the energy that the motor is using and the motor power that is installed (50, 75 or 100%). Note the steeper slope of the red line indicating the stiff shelf, where drag is plausible playing an increasing role when the motor power and thus the frequency is increasing.

With the measurements being valid, the results show that the energy consumption of the shelves is ranging from 3.144 – 12.29 Watt, rejecting the overload of the stiff shelf at 100% motor power. The energy consumption of the fins is ranging from 3.456 - 12.82 Watt. The energy consumption of the pump is shown in Table 1 and interesting to appraise.

Table 1: The energy consumption of the mechanical pump used for calibration of the self-constructed flow meter. Volumetric flow rates (m^3/min) are calculated by dividing the pump water flow generation (L/h) by 1000 and by 60 to translate to m^3/min for easy comparison to the other flow experiments. The energy consumptions are measured with an energy consumer device and match the values in the manual of the pump.

Volumetric flow rate (m^3/min)	Energy consumption (W)
0.0667	20
0.0933	35
0.1017	54
0.1217	68
0.1333	84

Setting the results off to each other, it shows that the oscillating fins (and shelves) consume 80-90% less energy than the pump for generating the same range of flow rate in the TinyOcean. Although the ways of generating flow are totally different, the gap is significant.

Figure 25 gives a detailed overview of the energy consumption results per shelf and fin.

Flow velocity (m/min) was calculated as 1m / (average time of ten measurements with pvc-tube / 60). The propagation of uncertainty was determined by first calculating the flow velocity plus and minus the standard deviation of the average time of ten measurements with pvc-tube. Then, the sum of the deviation of those two values was calculated for all the three motor power experiments and with this, the mean standard deviation of the flow velocity was assessed.

The results are quite distributed in the mentioned range of energy consumption. Remarkably, the stiff shelf is using comparable quantities of energy at 50% but significantly more energy at 75% compared to the fins and flexible shelf. It can be assumed that by the lack of flexibility, the surface pressure is distributed very badly resulting in high drag forces. The higher the motor power, the higher the frequency leading to more drag and increasing energy demand. Rejecting the 100% measurements, the fins overall have comparable energy consumptions.

Considering the standard deviations of the average time per meter flow, a few results stand out. First, the large fin showed both in the deep water column as in the shallow water column the smallest mean standard deviations (1.492 and 0.8463 respectively). Assuming these deviations are related to the presence of turbulence, because wobbling of the pvc-tube induced by turbulent water is of negative influence on the time it takes for moving one straight metre, this would be in favour of the large fin.

In general, the measurements in the shallow water column resulted in smaller error intervals than in the deep water column, indicating that the non-laminar movements in the water created by the oscillating regulator are fading away until a stable flow continues through the flume. This is visualized with the adding of a litre of dark green coloured algae in the area of the oscillating fin. The colour immediately fades out and travels as a green gradient through the TinyOcean, leaving clear water colour behind since the whole water column is moving in the same direction. A video of this process is accessible via Appendix 2.

Next to that, an accidentally observation was that behind objects laying on the bottom of the TinyOcean (flat oysters in this case), there are narrow long lines of dirt visible. This indicates a constant flow moving laminar-like in the same direction. Turbulent water would have disrupted these patterns.

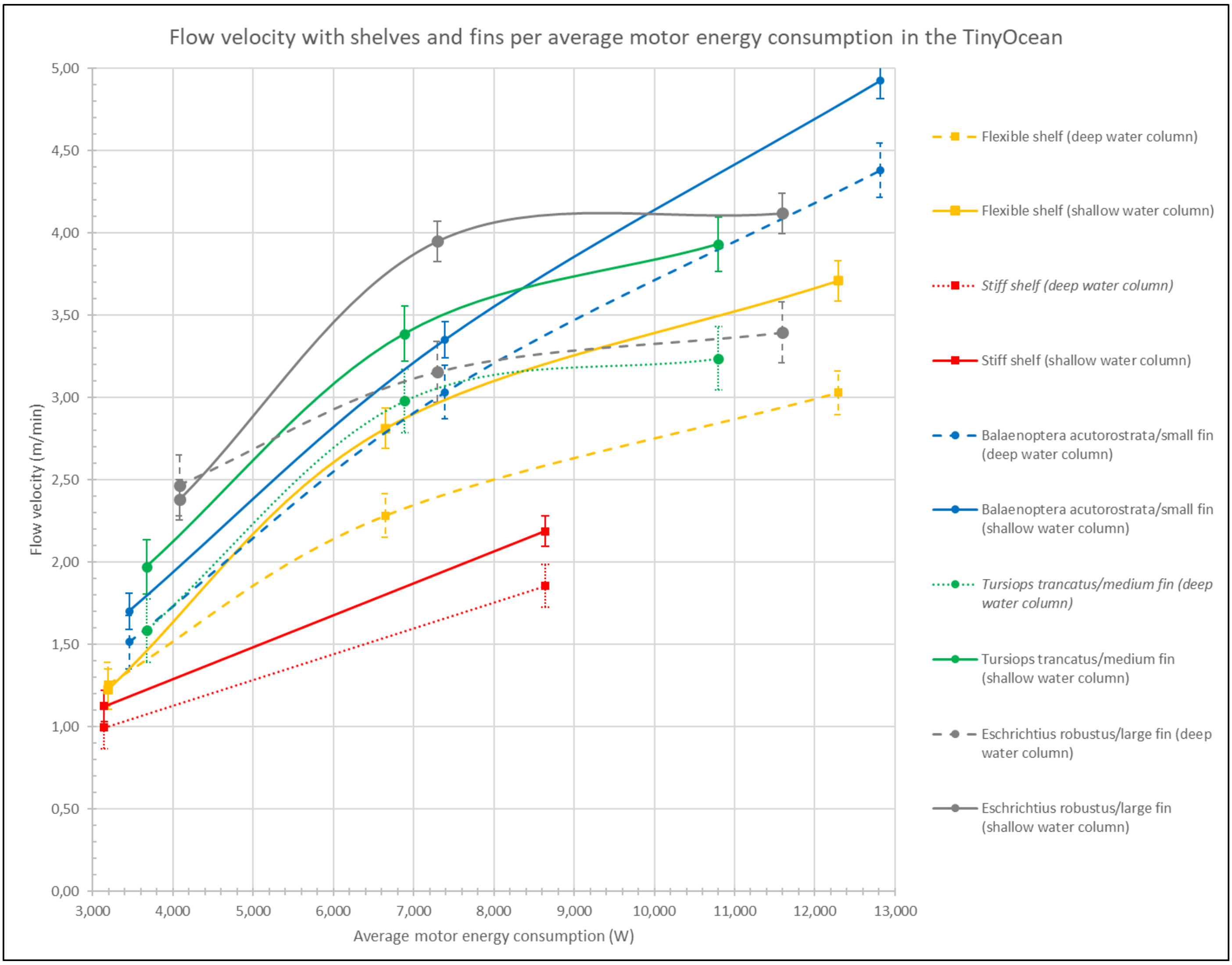

Figure 25: Generated flow velocity using the shelves and fins at 50, 75 and 100 percent of the oscillating regulator's motor power. Dashed lines: measurements in the deep water column. Solid lines: measurements in the shallow water column (see Figure 3). The mean standard deviation bars of the measured flow velocity are slightly overlapping, which lowers the confidence to conclude there is a faster flow velocity in the shallow water column. See description Figure 23 for an important note about the stiff shelf and medium fin in the deep water column. Remarkably, rejecting the 100 percent motor power measurements, out of the three fins only the large fin's flow velocity error bars are not in overlap with any other measurement. For the TinyOcean, it is best to be at the top left of this figure, where the flow velocity is the highest with the smallest energy need. Considering this, the large fin comes the closest, especially in the shallow water column.

The null hypothesis "no difference between shelves and fins" can be rejected concerning the stiff shelf, because the stiff shelf generates a much slower water flow with the same motor input and there is clearly no overlap between the confidence intervals of this shelf and the fins. Although there is no overlap with the results of the stiff shelf, there is some overlap with the flexible shelf. The flexible shelf has overlap with the error bars of the fins measured in the shallow water column. It appears that difference in shape (rectangle vs fin) is not yet sufficient to come close to the efficiency of the fins, the amount of flexibility (hardboard vs rubber) is also important and adds up to the results of the bio-inspired properties.

Frequency and amplitude

Another calibration of the method: the frequency acts similar between the different experiments and tends to a linear correlation with the motor power, independent of the fin or shelf (Figure 26). Frequency was determined using metronome sounds, audible in the videos accessible via Appendix 2.

But next to the frequency, the amplitude is interacting with the motor power as well. The shelves and fins are eccentrically attached to the end of the lever. A longer fin (bigger chord length) will shift the centre of gravity more outwards, causing a greater energy demand in order to facilitate the oscillating movement. Indirectly, the frequency will decrease with an increasing chord length and surface area.

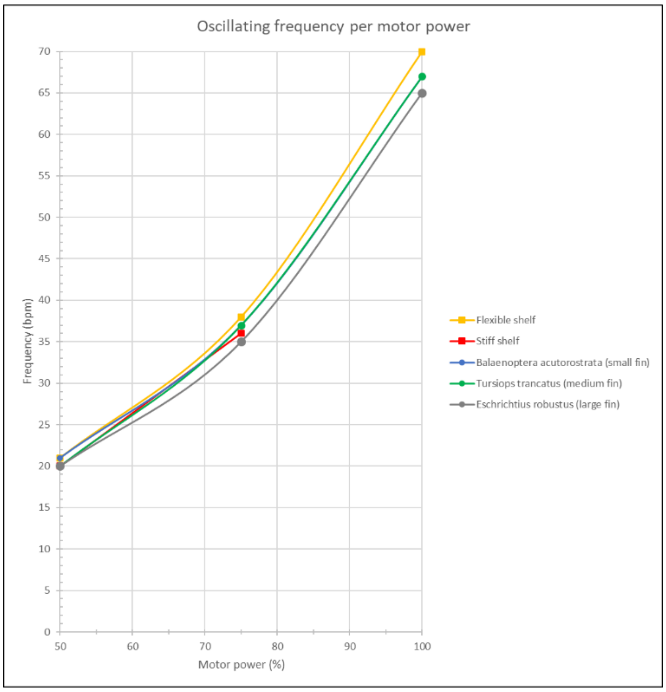

Figure 26: Observed frequencies per oscillating shelf and fin at different motor powers. The frequency was measured with metronome sounds.

The amplitude does act different depending on the fin or shelf in contrast to the frequency (Figure 27). Notice that the water column at the part where the regulator is placed is 45 cm deep (except for the stiff shelf and the medium fin, there it was 51 cm deep). The small fin has the greatest amplitude, it even breaks the surface and touches the bottom in the TinyOcean. This will cause wild water but will also move the whole column.

Remarkable is the flexible shelf. This design only gets flexible enough to "swing" towards a greater amplitude when the motor power is turned up.

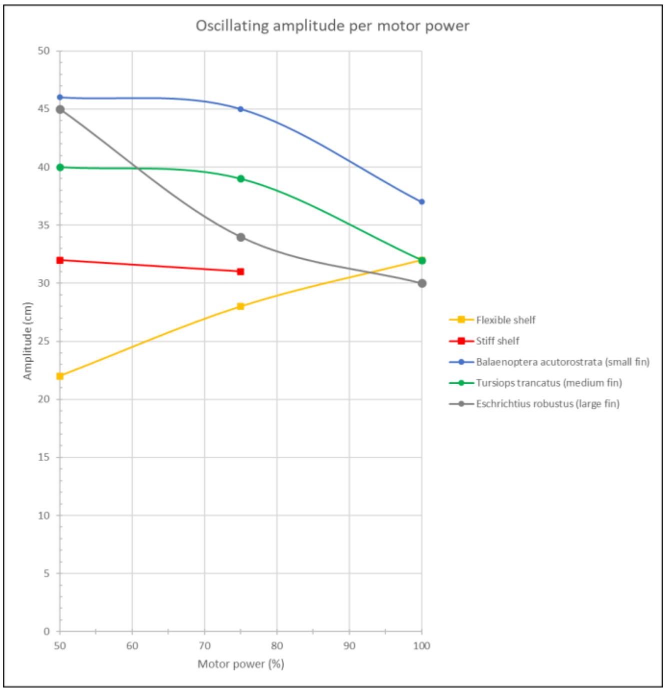

Figure 27: Measured amplitudes for the shelves and fins (using tapeline on the side of the wall in the TinyOcean) per motor power.

When the graphs in Figures 26 and 27 are combined, the large fin clearly acts differently than the other two fins (Figure 28). Only on a frequency of about 20 beats per minute, the amplitude is high enough to move the whole water column at the same time (45 cm high). When the frequency is increased the smaller fins will win regarding the amplitude.

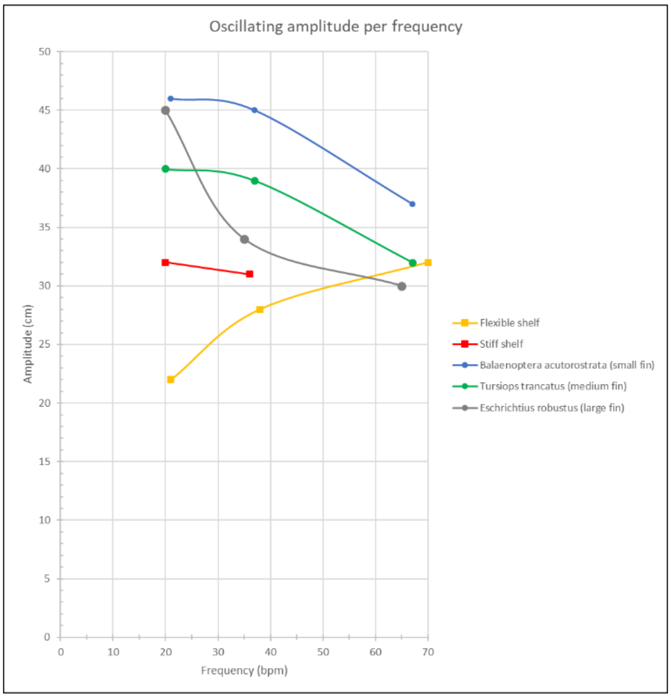

Figure 28: Combination of the frequency and amplitude for every fin and shelf, visualizing the effects of having chord-wise and span-wise flexibility. The fins are acting different in the range of motor powers.

Rejecting the 100% measurements, the shelves show smaller amplitudes than the fins. This suggests that the fin shape with chord-wise and span-wise flexibility effectively reduce drag and oscillate smoothly.

Discussion

As discussed in the introduction, the decision to mimic the characteristics of a bio-inspired underwater fin to mechanically create a water flow should be made with caution. In contrast to the multifunctional tail fins in nature, this project aims to optimize for a single function to reach the engineering goal. That suggests that the shape and flexibility of the fin probably still can be improved when only focussing on the specific function. Mechanical impellers and propellors are huge creators of turbulent water. However, it would be valuable to quantify the flow kinematics of this as well.

Also, the pump is a totally different flow mechanism than the oscillating device and was sucking in the water through a narrow opening. This creates pressure differences in that area and makes the measurements with the pump not fully trustworthy to compare with the oscillating shelves and fins.

Beside, this project should perform the flow rate experiment again with the stiff shelf and medium fin in the deep water column, because of the changed water depth that made these measurements unusable. However, big changes in the results are not expected. The used flow meter is validated but still self-constructed and interpreted by hand, increasing the inaccuracy. Focus on the Ultrasonic Flow Meter would be better (transducer replacement or new purchase). This method has high potential and would be highly accurate. Next to that, by increasing the number of transducer pairs, or by performing measurements at different heights in the water column, it is possible to make a cross-sectional flow profile. Moreover, this method is non-intrusive, as nothing is inserted into the water column that is under measurement.

Furthermore, there should also be a method for quantifying the turbulence, like particle image velocimetry. With this, a flow profile can be made, and there can be explored at a technical level whether the presence of turbulence is related to standard deviation of mean flow (Jacobi et al., 2016). Next to that, for the context of this project, it should perform an experiment with real zooplankton and fish larvae to determine their survival rate at different flow situations. It is important to explore which range of Reynolds number they survive and what amount of vorticity they can handle. The reached Reynolds numbers are worth a try with living zooplankton and fish larvae to explore their survival rate.

Explore what will happen when the oscillating frequency is turned down by decreasing the motor power below 50%. When this does not solve the high Strouhal numbers, the adding of a second oscillating underwater fin in the opposite part of the TinyOcean is the best option to create the wanted smooth flow.

Perhaps a good bio-inspired way to decrease drag on the fin is adding tubercle structures at the leading edge where the flow bounces against the foil shaped fin. Tubercles of the flippers of *Megaptera novaeangliae* (humpback whales, see cover photo) are known to effectively separate the stream and create extra lift force with an decrease in drag and maybe even lower energy use (Fish & Lauder, 2006; Wei et al., 2015). However, the additional effect on vortex generation and Strouhal number should be determined as well. Another suggestion to reduce drag is to mimic the microgrooves skin structure of specific cetaceans and sharks that can influence the boundary layer in such a way that there is almost no friction, increasing efficiency (Fish et al., 2008; Fish & Lauder, 2006). Looking closely to nature can bring new improvements.

Conclusion

All organisms obey the laws of physics and the principles of evolution, making nature a very experienced designer. To generate a plankton and fish larvae saving water movement, inspiration from cetaceans led to the creation of an oscillating underwater fin that should beat the custom mechanical way of generating flow using impellers and propellors. This research has put this matter to the test using literature and a sequence of experiments. It can be concluded that, in the context of BlueLinked's TinyOcean, a bio-inspired oscillating underwater fin beats the mechanical way of generating a water flow and turns out to be significantly more efficient. It is very likely that this design will mix the water properly, transport the detritus to the purifying seabed and most important, will very likely leave the most fledging marine life intact. However, fully eliminating turbulence is not applicable, so reducing it to a minimum with Reynolds numbers under 4000 should be the goal. Further development of the 2D prototypes into 3D prototypes and follow-up research is needed.

It was hypothesized that the bio-inspired underwater fin would be more efficient and best suitable for generating a suitable flow in the TinyOcean, but there was a sceptical side note about the multifunctional trade-off that is happening in natural evolution of tail fins. This empirical analysis has showed that the underwater fin is using 80-90% less energy than the pump for generating similar flow rates in the TinyOcean. With this, the expectation has been exceeded. There is a complete lack of impellers and propellors in the natural ocean for a reason.

The biggest reason for the fin to be so energy efficient, is the distribution of pressure over the fin shape, pushing to the whole water column in a single sweep. Whereas an impeller is too centred and is putting a lot of effort in moving the water in multiple directions in a closed system.

Figures 23, 25 and 28 shows the effect of both shape and stiffness that differed between the shelves and fins. Shelves are less efficient than fins, they need fluke shapes and both chord- and span-wise flexibility to efficiently guide the water forward in stead of lifting the water column in a vertical way.

All the measurements at the 100% motor power setting of the oscillating regulator should be rejected, because of the visible out of context wild water movements it was generating and the damage it will do to the oscillating regulator. Taking this into account, the following conclusions can be made based on the literature and experiments comparing the three prototype fins:

- Fastest water flow velocity generation was with the large fin. At 50% motor power 2.380 m/min (deep) and 2.467 m/min (shallow) and at 75% motor power 3.156 m/min (deep) and 3.949 m/min (shallow).
- Considering the lowest energy consumption, all the three fins are winners, ranging in 3.456 - 7.392 W.
- Biggest amplitude was with the small fin, with 46 cm at 50% and 45 cm at 75% motor power. However, at 50% motor power, the large fin is moving the whole water column as well with an amplitude of 45 cm.
- Least amount of visual turbulence was with the large fin, apparent from the stable pvc-tube in the videos (Appendix 2), the smallest standard deviations of the average time and the lowest Strouhal number.

Taking these four parameters into account it can be concluded that the large fin, inspired by the shape and aspect ratio of the gray whale (*Eschrichtius robustus*) is the most efficient in context of the TinyOcean (Figure 29).

Gray whales are characterized by their slow and steady swim speed. That is why this species can afford to have a relatively large caudal fin area in order to generate more thrust per stroke. Although, the large surface area takes too much energy to sweep fast up and down through the water, which is not the case with a motor power of 50% and lower. Since BlueLinked only wants the water of the TinyOceans to be mixed and kept in suspension in such a way that all the dirt ends up on the purifying sandy bottom part, this fin adapted to calm propulsion seems ideal.

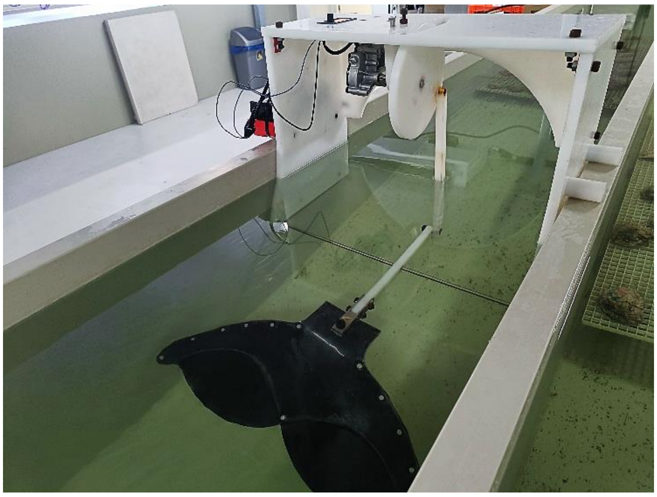

Figure 29: The large fin inspired by the gray whale (*Eschrichtius robustus*) at 50% motor power comes out as the most efficient option based on the experiments conducted in this project.

The meeting with Prof. Dr. Frank Fish, the referred literature and the findings during the dissection of real harbour porpoise caudal fins state that the peduncle is a key element for the propulsive efficiency of the fin. Due to the limits of this project, the function of the peduncle is not yet analysed and implemented in the design. Mimicking the peduncle joint (say with elastic bands or springs) will very likely increase the efficiency of the oscillating underwater fin even more by creating a dynamic angle of attack.

Creating innovations inspired by nature and realized by science, that is what happened in this project. In this first trial of the innovation, there is already reached a significant low input and high thrust by mimicking nature. With this pioneering research at the breeding center of BlueLinked, the author wants to contribute to the movement of efficient and sustainable marine aquaculture that humanity needs in this changing world.

Recommendations for BlueLinked

The author's advice to BlueLinked:

Use the large fin inspired by *Eschrichtius robustus* at motor power 50% to generate the water flow in the TinyOcean for the coming proof-of-concept till follow-up research proves better. With this fin on this motor percentage, the volumetric flow rate in the centre of the water column is around 0.58 m^3/min with a velocity of around 2.424, assuming the water column is moving as a whole. A full round in the centre of the TinyOcean is 19.6 meter ($length\ 7975 \cdot 2 + \pi \cdot 2 \cdot radius\ 587 = 19638\ mm$). This means that all the 4263 litres in the flume of the TinyOcean in theory are making a circle in 8.1 minutes ($19.6/2.424 = 8.1$), resulting in more than seven full cycles per hour.

However, the requirements for the flow depend on the needs of the organisms or fish species that are hatched and cultivated. When there is a need for a faster flow, other fin shapes should be considered instead of turning up the motor power on the oscillating regulator. It is best to review this per specific situation. In addition, it is good to consider implementing a second oscillating fin in the TinyOcean.

Next, work on a 3D-model of the fin, implementing the foil shape and maybe even the tubercles on the leading edge as discussed in this thesis. Using a 3D-printer with flexible filament could work, probably forced to multiple pieces because of the size limits of a 3D-printer. Perhaps, a mould can be made from the 3D-print. Research for the right material should start. It needs to have the right stiffness, right density, without chance of leaking additives and resistant to degradation by saltwater and UV-light. To avoid becoming a source of microplastics in the system, a biodegradable material would work best. For this part, maybe Prof. Dr. Frank Fish can be consulted again.

Once the 3D prototype is made, it should be tested in laboratories specialized on hydrodynamics. Possibly a good collaboration opportunity would be with the lab of BlueLinked's previous connection in biological fluid mechanics Xiaoyin Fang, a PhD student of the Faculty of Science and Engineering at the University of Groningen, or with the Royal Netherlands Institute for Sea Research (NIOZ).

Lastly, to match the sustainable ideas of BlueLinked, a future goal should be to design an alternative to set the fin in motion without using electricity. Perhaps inspired by muscle fibers. Make it easy to handle, life-like and environmentally friendly.

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Appendices

1: Transcript meeting Prof. Dr. Frank Fish

After some email exchanges an online meeting was scheduled on the 4th of February 2022. After some introductory talk and explanation of the project using some PowerPoint slides, the meeting went as follows:

"Do you think a fin will be the best application for generating the water flow we want?"

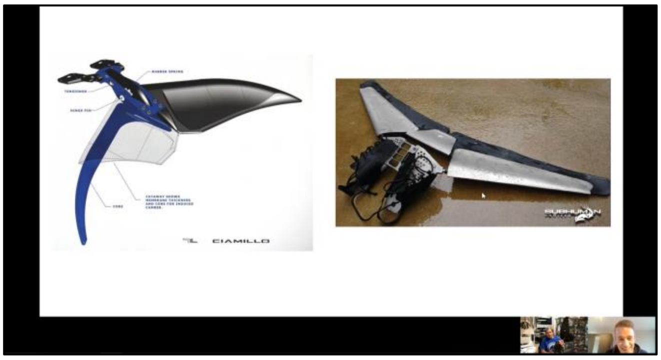
'At the speed you are talking about an impeller might be fine, although you do get a certain type of radio flow with that. With the fin, if it is in sort of midwater, you can probably push the water very well and there will be some degree of vorticity particularly at the tips. Although, that will be near the wall itself and not in midstream. So, the tip vortices, which will be concentrated, will be towards the walls so probably won't have much bearing on things. It depends whether you do this with some rest in between strokes or in a continues stroking action. There probably will be some vorticity there but talking about a very low flow of around 0.02 meters per second, this won't disturb the fish larvae that much.'

"Vorticity is like turbulent water, is that right?"

'Vorticity is not turbulent per se, it is organized. For turbulence we consider that the flow is radic and chaotic. In vorticity, what you get is simply a change in flow. At the end of the tank, the flow is wrapping around, because the flow is travelling in a straight line towards a turn where it moves around and creates vorticity. But the formation of an actual vortex is more of a cyclonic organized type of flow, that is not necessarily turbulent or laminar. But, at these slow flow rates it is probably not going to matter too much. I think it is interesting to have another way of doing it. The question becomes from the standpoint of the energetics. How much energy do you have to put in? Probably this is fairly minor. The efficiency of movement can be greater than what you would have for an impeller, so that ability to move the water would be more efficient. Although, because the sort of periodicity rather than spinning around, I don't know what the electrical consumption would be.

Also, I would probably tend to put that oscillating fin maybe halfway down, because going through a rapid turn, because you have just a plate there and the flow must wrap around really quick and you don't want it then to go into an accelerated flow for the larval fish. The main goal is to not damage these larval fish. Beyond that, the question becomes what is the setup that you can have this oscillating fin and what is the longevity of it. We know a lot about impellers and propellors and they can work for extended periods of time, whether this oscillating fin can also do it. Essentially, it is another solution to try to move your water. And this particular solution might work perfectly well. Probably the rate of which you oscillate the fin isn't going to be very high. Whatever you do, I would have started on a real stat and then make measurements of flow as you go through. Because it is very broad, it is going to be able to push a lot of water all at once. Whereas an impeller, if it is small, you have to accelerate it, so it has a higher spin rate. So, I mean the fin is one particular solution. Whether it will be better than an impeller or not is difficult to say at this time until you do some testing.'

"I have some specific questions about the Lunocet…"



'Oh yeah, I have got one here. I worked on this initially with Ted Ciamillo who basically then went off. So, what you are looking at on the right is an early version of it and then he made the one with a bit more flexible fin and something that looks a bit more like a dolphin tail.

"Yeah I think it really makes sense. Can you explain how you came up with the design of the Lunocet?"

'I got another fin. I originally showed Ted when he came to my office and lab a monofin that another inventor came up with called the Dolphin. So, this is the originally Dolphin and an inventor came to me because in Europe they have monofin races, they are quite popular, and he wanted to go behind the typical monofin and utilize the bases of a dolphin, so he developed this. Unfortunately, he spent a lot of money, and it didn't went very good, the rubber is falling apart, he had it made in Taiwan but it was not very good. There is a certain degree of flexibility to it, which is something you might consider, how much flexibility you want in your fin. Anyway, based upon that, Ted decided to build the Lunocet and, actually, Ted builds light-weight bicycle brakes. So he has CNC machines in his basement and then the Lunocet is attached with bicycle shoes, that is what he knew best.

Now the advantage of the Lunocet over the Dolphin was that you actually had a mobile joint here, whereas the dolphin goes directly on your feet. And because your feet don't normally bend back or sort of plantar flex to a high degree not like your wrist. The dolphin was somewhat limited. Even with the Lunocet, the problem is still that I don't think he is getting enough of the angular change that you need at that joint, the same way that I can move my wrist here. It is still somewhat limited, you can move it more in way than up. So, that is something to build in to the joint.'

"So that is what you meant with there could be some modifications for the Lunocet?"

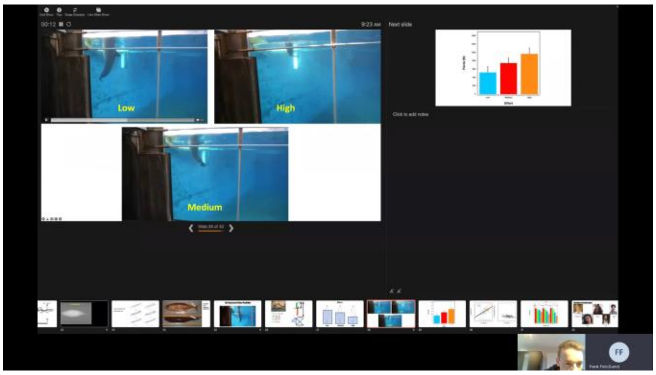
'Right. That and also the materials you are going to work with. And how much flexibility there is. When dolphins, actual real dolphins, swim the flukes will bend. And it bends for a couple of reasons. So, we have a spine that goes down the animal. Right here, where you can see the fin come in to the body, the vertebrae are such that they allow greater flexibility there. So it is like, there is an extra joint. So as this is going up and down, the fin is not just wagging like that, it also is bending right at that joint right there, we call it the peduncle. Because that joint that allows the flexion is just a little posterior of where the fin comes into the body, it tends to bend the flukes itself. So, there is some flexibility.'

"So maybe it makes sense if I mimic the peduncle part as well."

'Right, well let's just put in an extra joint. That is all that is required there.

"But there is flexibility spanwise or also chordwise?"

'Both. Both. Let me just show you something. I will share my screen.



So, these are tail stands. And if you look, you can see that the tail is wagging and the flukes themself actually bend. Let's just take a look here. You can see that the fluke is bent in the sort of low one. The flukes bend and they bend in a chordwise fashion and also in a spanwise.

Let me get another fluke, this is a prosthetic fluke for an animal called Fuji. That was in Japan, Fuji died, and the Japanese had a prosthetic fluke made because it still had a stump. Recently in the United States we had another animal called Winter, and they made a prosthetic fluke for Winter. It is a famous story, there is even a movie. So, what happens is, on the downstroke, the tips of the flukes will actually bend up. And then as we go into the upstroke, they bend down a little. So there is some degree of flexibility spanwise, although the main axes here remains very stiff and straight, it is only the tips. And then there is chordwise bending also, because again that joint is behind the anterior insertion, so it is here and bends the entire tail which then bends the fluke. We are not sure if this really increases the efficiency, we think it does, but we are not sure about the whole thing because I am basically dealing with dolphins and it is hard to do any sort of manipulations on them. We have looked at the structure of the flukes in such and looked at bending where we just take flukes from dead dolphins and bend them up. And it appears, there is more and more literature that basically says that there is an increase in efficiency, propulsive efficiency, due to chordwise as well as spanwise flexion.'

"Okay, that sounds quite essential. And about the fin, one thing is certain, the span width of my fin will be 22 inches. What do you think is the most efficient, if I make a high aspect ratio fin or a low aspect ratio? So, like a small chord or like a longer monofin? I want to make a really slow flow."

'Well, I don't think the slow flow is the problem, I think the bigger thing is the efficiency. As you beat this fin up and down at a slow rate, what is the most efficient way of doing it? Do you introduce any sort of flexion into it? Do you have a non-stiff material and how long will that material last? You know, that becomes an important thing. If you build something out of metal, you know like a propellor or what not, it is going to last a long time. The biggest problem will be getting it to rotate and turn and whether that be becomes fault or not. It is hard to say. Whit a fin you can have a go, but how often do you have to replace it, because you may use something other than a metal, you may use some sort of rubber or silicon or something like that to produce your fin. And then give it some degree of flexion and so, the problem then becomes how stable is that. I mean, considering that fin that I showed you for Fuji the Japanese dolphin, that was made by Brick Stone Tire. Brick Stone is a Japanese company and they have knowledge of rubbers, and this fin is actually from a type of rubber probably a type based on automobile tires. So there are rubbers that you could have that will stand up over time, as car tires do for extended periods of time. And I can show you, the big problem is, you can see cracks. So, the rubber that was made for this wasn't very good and this just degraded over time, not from wear, just time. And even the Lunocet, this tip here, I actually glued it back, but it started to go also a little bit of cracking there. The material that you use is going to be important, because it is not going to be under real high load or stress, but over time in saltwater and such how long is it going to last before it starts to fall apart and you have to replace it. Now, probably that will be a very long time.

But, I think there are other reasons to do a biomimetic approach and that is if the efficiency is greater, then it is going to cost less to run the entire operation. But there is also a public relation sort of thing. You are trying to increase populations of fish, a main just there is for human consumption we want things like cod, what we depleted. But from a conservation standpoint it also makes for a healthier ocean. The idea of biomimicry placed into that as a sort of narrative that you are doing something that basically costs less to run it is more economical and you are introducing a sort of natural concept into the whole thing. So, there are various reasons to do it.

Like a say, at the speeds we are talking about, impellers may not be a bad solution on themselves, propellors have been around for a long time. But they will continuously fill that space and the fish will have to negotiate around it. So, whether they get chopped off even at low speeds, is something to consider. I mean, birds do fly into windmills, you have this spinning thing with very broad areas. So here if you have this slightly moving fin, at one time you get a flow which nothing is touching the fish and then go through, so there is more room for the fish to actually circulate around. Opposed to an impeller where essentially, they are going to get caught up in that even at low speeds, because you got the blockage you know. The impeller is filling in that entire area.'

"But when it comes down to the material, you should suggest look to nature and the bio-inspired way of doing it as well?"

'Well, for proof-of-concept I would just 3D-print something in hard plastic and then try that out to see how it, once you get the gearing right and those joints, actually pushes the water. Then you can print in some sort of less stiff medium, some sort of rubber. But something that is too flappy won't be very good.'

"Oh yeah we can experiment with that. And what about the surface, do we want a really smooth surface or a bit rough surface like a shark skin for example?"

'It depends on what else you have in there. You say you have a lot of larvae and food, are there barnacle larvae?'

"It is going to be quite a murky water, there is a lot of algae in there as well."

'Okay, I am not too worried about the algae, I am more worried about barnacles and even mussels. Things that will attach to the walls and will attach to the fin. If it is algae, I am not particularly worried about things, although you may get collections of algae on the surfaces. So that gives maintenance, you going to have to clean and scrape it or some like that. Or filter the water periodically.'

"Yeah, we don't really filter. The cleaning part of the tank is the sand on the bottom and underneath we suck out the water and we let the water flow again really slow in the tank. So we make sure it is not anoxic, but the micro-organisms in the sand are cleaning the water."

'Yeah okay. Well, I will go for a smooth surface of the fin at this point. But I would recommend anything.'

"Do you have a good idea to measure the turbulence of the flow I generate?"

'Uhm, the way we typically do that is by some type of particle visualization. Depends on the water clarity and what particles that you have that you can illuminate in some way.'

"And how about the velocity of the water?"

'Oh, there are various velocity meters. Some are just simple little impellers.'

"But does that work at a really slow speed?"

'Yeah it can work at really slow speeds. But, things I have been using, there is a company Marsh McBirney, they produce flow meters. So, let me see if I got one here. This one is by a company Hach, in Loveland Colorado. It is electronic. Stick this in the flow and then you read off on a screen. It should be sensitive enough. It does not matter whether it is saltwater or freshwater, it will work in both. And I am sure there are probably in Europe some versions of this by some other companies.'

"Okay that is the way to go. I mean, I can design a fin but I want to know if it is efficient, so I have to measure everything. Also, the BlueLinked company wants me to 3D-model the fin. Do you have experience with suitable software to 3D-model certain shapes? I was working with the half of an ellipse shape because it is just easy to do the math, but that would not be the most efficient shape of course so I want to 3D-model it."

'Funny you say that, right now I am trying to do a 3D-print and the printer is not working and I am trying to contact the company. Uhm, let's see, I am wondering if I have a STL file I can just send you of a fluke. I will send you the one of the harbour porpoise.'

"That would be amazing, thank you."
"I am happy I could talk to you. If I have any more other questions, can I reach out to you again via email?"

'Yeah, just email me, that is not a problem.'

"Okay, perfect. I will finish this project somewhere in the summer, so I have like six months left and I will let you know the results, I think it is quite fun. Do you have any final tips for my project?"

'No, not really, the big thing is that you make sure that you have a joint in there that allows for pitch control. As well as then something that allows you to heave the entire structure.'

"I agree that is important. Okay, I have a lot of information, thank you so much, and we will stay in touch."

'Okay, very good, good luck and have fun!'

2: Supporting pictures and videos

This project obtained a bulk of imagery (and data) supporting the conducted experiments and findings. To reach out to these files, the author can be contacted via the email address on the second page of this thesis:

m.c.h.bas@students.uu.nl

There is also a repository with all the files on the cloud of GitHub. As long as available, this public shared space is accessible via the following link:

https://github.com/MennoBas/BlueLinked.git

3: Logbook

This Major Research Project took 36 weeks, from the 15th of November (2021) to the 29th of July (2022). All the relevant and notable events are listed in the logbook below.

15-11-2021	Kick-off visit BlueLinked with Jaco and Madalena Pena, first meeting with Michaël
16-11-2021	Lecture about wave attractors from Leo
17-11-2021	Meeting with Leo (online)
18-11-2021	
19-11-2021	
(weekend)	
(weekend)	
22-11-2021	
23-11-2021	Meeting with Leo
24-11-2021	Meeting with Jaco
25-11-2021	Present at BlueLinked
26-11-2021	
(weekend)	
(weekend)	
29-11-2021	
30-11-2021	Meeting with Leo
1-12-2021	
2-12-2021	Present at BlueLinked + first meeting with Nico Leeuwestein
3-12-2021	
(weekend)	
(weekend)	
6-12-2021	
7-12-2021	Meeting with Leo
8-12-2021	
9-12-2021	Present at BlueLinked: watched a documentary about aquaculture in The Netherlands with the team
10-12-2021	
(weekend)	
(weekend)	
13-12-2021	
14-12-2021	Meeting with Leo
15-12-2021	
16-12-2021	Present at BlueLinked: experiment to confirm there is no stratification in the big tank (viewing temperature and salinity)
17-12-2021	
(weekend)	
(weekend)	
20-12-2021	
21-12-2021	
22-12-2021	Meeting with Leo (online)
23-12-2021	
24-12-2021	

(weekend)	
(weekend)	
(Christmas break)	
(Christmas break)	
(Christmas break)	
(Christmas break)	
(Christmas break)	
(weekend)	
(weekend)	
3-1-2022	
4-1-2022	
5-1-2022	
6-1-2022	
7-1-2022	
(weekend)	
(weekend)	
10-1-2022	
11-1-2022	
12-1-2022	Meeting with Leo (online)
13-1-2022	
14-1-2022	
(weekend)	
(weekend)	
17-1-2022	
18-1-2022	Meeting with Leo
19-1-2022	
20-1-2022	Present at BlueLinked
21-1-2022	
(weekend)	
(weekend)	
24-1-2022	
25-1-2022	
26-1-2022	
27-1-2022	Present at BlueLinked: experiment with a monofin from the swimming pool for orientation on the shape and material
28-1-2022	
(weekend)	
(weekend)	
31-1-2022	
1-2-2022	Meeting with Leo
2-2-2022	
3-2-2022	Present at Blue Linked + visit "Van Valkenburg Metaal en Techniek B.V." in Bodegraven with Nico Leeuwestein
4-2-2022	Meeting Prof. Dr. Frank Fish from the USA (online)
(weekend)	
(weekend)	
7-2-2022	
8-2-2022	Meeting and evaluation with Leo (online)

9-2-2022	
10-2-2022	Present at BlueLinked + meeting with Michaël, Tim van Veenendaal, Floris de Veld and Mark van den Berg about the making of the oscillating regulator
11-2-2022	Interim Assessment
(weekend)	
(weekend)	
14-2-2022	Present at BlueLinked: helped with installing the second and third TinyOcean at Blue Linked
15-2-2022	
16-2-2022	Present at BlueLinked
17-2-2022	Present at BlueLinked, with cakes for my birthday
18-2-2022	
(weekend)	*(in isolation due to COVID)*
(weekend)	*(in isolation due to COVID)*
21-2-2022	*(in isolation due to COVID)*
22-2-2022	*(in isolation due to COVID)*
23-2-2022	*(in isolation due to COVID)*
24-2-2022	*(in isolation due to COVID)*
25-2-2022	
(weekend)	
(weekend)	
28-2-2022	Present at BlueLinked
1-3-2022	Meeting with Leo + hop on hop off around stores searching for the right material for the first prototypes
2-3-2022	Present at BlueLinked + visit "Groen Rubber Rotterdam B.V." in Rotterdam for (free) prototype material
3-3-2022	Present at BlueLinked
4-3-2022	
(weekend)	
(weekend)	
7-3-2022	Present at BlueLinked
8-3-2022	Meeting with Leo
9-3-2022	
10-3-2022	Present at BlueLinked
11-3-2022	
(weekend)	
(weekend)	
14-3-2022	Present at BlueLinked
15-3-2022	Meeting with Leo
16-3-2022	Meeting with Mark van den Berg and Floris de Veld (online)
17-3-2022	Making of the first prototypes
18-3-2022	Making of the first prototypes
(weekend)	
(weekend)	
21-3-2022	Present at BlueLinked: making a tool to oscillate the fins by hand + making underwater videos of the first prototypes

	in the swimming pool in Zeist with Jan Becker
22-3-2022	
23-3-2022	Stiffness experiments with the first prototypes in the physics lab from Utrecht University with Rudi Borkus
24-3-2022	Present at BlueLinked
25-3-2022	
(weekend)	
(weekend)	
28-3-2022	Present at BlueLinked + purchase of polyethylene at HORNBACH Nieuwegein for reinforcing the first prototypes
29-3-2022	Meeting with Leo
30-3-2022	Meeting with Rudi Borkus
31-3-2022	Present at BlueLinked: helped with settling down hundred flat oysters in one of the TinyOceans
1-4-2022	
(weekend)	
(weekend)	
4-4-2022	Experiments with two recently stranded harbour porpoises at the Pathology department from the Veterinary Pathological Diagnostic Center (VPDC) of the Faculty of Veterinary Medicine of Utrecht University + meeting with Rudi Borkus before and after
5-4-2022	Meeting with Leo
6-4-2022	Present at BlueLinked
7-4-2022	Meeting with Jaco and Madalena Pena
8-4-2022	
(weekend)	
(weekend)	
11-4-2022	Present at BlueLinked
12-4-2022	
13-4-2022	
14-4-2022	Making of the reinforcement of the reinforced prototypes
(Easter break)	
(weekend)	
(weekend)	
(Easter break)	
19-4-2022	Meeting with Leo
20-4-2022	Present at BlueLinked: making of the reinforced prototypes
21-4-2022	Present at BlueLinked: set correct data in ultrasonic flow meter
22-4-2022	Stiffness experiments with the reinforced prototypes in the physics lab from Utrecht University with Rudi Borkus
(weekend)	
(weekend)	
25-4-2022	Present at BlueLinked: improving the tool to oscillate the fins by hand + making underwater videos of the reinforced

	prototypes in the swimming pool in Zeist with Jan Becker
26-4-2022	Meeting with Leo
(King's Day)	
28-4-2022	Present at BlueLinked: trying to fix the ultrasonic flow meter with Tim van Veenendaal
29-4-2022	Retirement party from Leo at the Utrecht Botanic Gardens
(weekend)	
(weekend)	
2-5-2022	Present at BlueLinked: different flow rate experiments with ping pong balls
3-5-2022	Meeting with Leo
4-5-2022	Present at BlueLinked: different flow rate experiments with ping pong balls
(Liberation Day)	
6-5-2022	
(weekend)	
(weekend)	
9-5-2022	
10-5-2022	Meeting with Leo
11-5-2022	Present at BlueLinked: different flow rate experiments with ping pong balls + experiment with electromagnetic flow meter
12-5-2022	Present at BlueLinked: experiment with electromagnetic flow meter
13-5-2022	
(weekend)	
(weekend)	
16-5-2022	
17-5-2022	Meeting with Leo
18-5-2022	Meeting with Rudi Borkus
19-5-2022	Present at BlueLinked: experiment to determine the sedimentation rate of detritus in the water column
20-5-2022	Present at BlueLinked: first time combining the oscillating regulator and the reinforced prototypes with Mark van den Berg and Floris de Veld and everyone else present at BlueLinked --> from this moment on, the whole system remains in operation in one of the TinyOceans + experiment with electromagnetic flow meter
(weekend)	
(weekend)	
23-5-2022	Present at BlueLinked: experiment with electromagnetic flow meter
24-5-2022	Meeting with Leo
25-5-2022	Present at BlueLinked: presenting my project to the board of The Wadden Fund and Foundation Oceans at Work + experiment with electromagnetic flow meter
(Ascension Day)	Present at BlueLinked: experiment with electromagnetic flow meter
27-5-2022	Present at BlueLinked: experiment with electromagnetic flow meter
(weekend)	
(weekend)	
30-5-2022	Present at BlueLinked: experiment with electromagnetic flow meter + making of the stiff shelf
31-5-2022	
1-6-2022	Present at BlueLinked: visit by Leo and Jaco
2-6-2022	Purchase of nylon bolts and nuts at Isero Zeist for finetuning the reinforced prototypes
3-6-2022	Present at BlueLinked: finetune of one of the fins + experiment with electromagnetic flow meter
(weekend)	
(weekend)	
(Pentecost break)	
7-6-2022	
8-6-2022	Present at BlueLinked + meeting with Leo (online)
9-6-2022	Present at BlueLinked: experiment with self-constructed flow meter
10-6-2022	
(weekend)	
(weekend)	
13-6-2022	Meeting with Leo (online)
14-6-2022	Purchase of more nylon bolts and nuts at Isero Zeist for finetuning the reinforced prototypes
15-6-2022	Present at BlueLinked: cleaning and finetuning the other two fins + trying of different ideas for a self-constructed flow meter + meeting with Rudi Borkus
16-6-2022	Present at BlueLinked: experiment with self-constructed flow meter
17-6-2022	Present at BlueLinked: experiment with self-constructed flow meter
(weekend)	
(weekend)	
20-6-2022	
21-6-2022	Present at BlueLinked: making the flexible shelf + experiment with self-constructed flow meter
22-6-2022	
23-6-2022	
24-6-2022	
(weekend)	
(weekend)	
27-6-2022	
28-6-2022	Final Presentation at the IMAU Climate Physics end-of-year master research symposium of Utrecht University (Leo and Michaël assessing)
29-6-2022	Present at BlueLinked: final Presentation for everyone present at BlueLinked with Jaco joining online (and assessing) + first weekly team meeting

30-6-2022	
1-7-2022	
(weekend)	
(weekend)	
4-7-2022	
5-7-2022	
6-7-2022	Present at BlueLinked: team meeting + finetuning of the oscillating regulator
7-7-2022	
8-7-2022	
(weekend)	
(weekend)	
11-7-2022	
12-7-2022	
13-7-2022	Present at BlueLinked: team meeting
14-7-2022	
15-7-2022	
(weekend)	
(weekend)	
18-7-2022	
19-7-2022	Meeting with Leo (online)
20-7-2022	Present at BlueLinked: team meeting
21-7-2022	
22-7-2022	Deadline concept Thesis to Leo and Michaël (for the last points of feedback)
(weekend)	
(weekend)	
25-7-2022	
26-7-2022	
27-7-2022	Present at BlueLinked: team meeting
28-7-2022	
29-7-2022	Deadline final Thesis to Leo, Michaël and Jaco