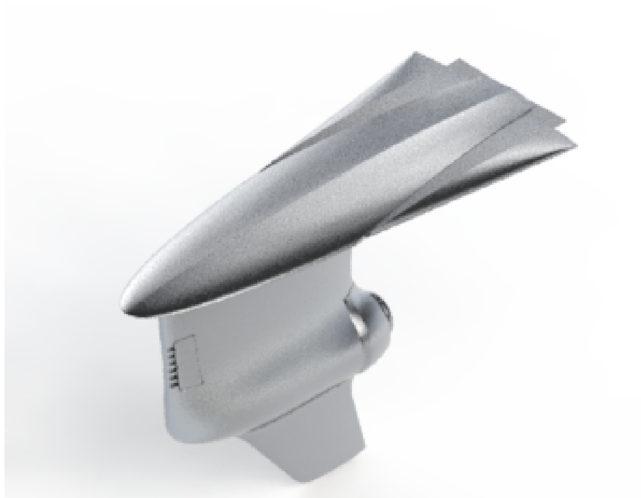

Anti-Ventilation Plate Optimization

A collaboration between Chalmers University of Technology, Pennsylvania State University, and Volvo Penta

Bachelor's Thesis IMSX15-21-14

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Cover: CAD rendering made of the assembled, leading anti-ventilation plate within Solidworks (2020); plate modeled by Emil Nilsson and rendered by Matthew Coleman.

Gothenburg, Sweden 2021

Abstract

With the increasing electrification within the boating industry, problems associated with low energy-dense batteries arise. With the desire to increase mileage while reducing battery size, the need to save energy is larger than ever before. This has led to an extensive demand of minimizing the overall resistance of each part used within a boat's schematic; in this case, a sterndrive powered by an electric outboard motor. This project investigatd ways to optimize hydrodynamic performance of the anti-ventilation plate, which prevents surface air from being drawn into the system's propeller.

The objective of this project was to generate and analyze a number of innovative anti-ventilation plate (AVP) design concepts through objective engineering practices which would supply Volvo with data and ideas for further considerations on future development. This project required a thorough understanding on outboard engine anatomies, boat design, hydrodynamic understanding of planing hulls, and computational fluid dynamics. This knowledge was attributed to the team's independent research and close contact with industry experts and supervisors.

The study further considered the identification of customer needs and the idea generation process; where these processes were supplemented by the team's initial research, ultimately allowing them to generate a multitude of unique features and concepts. Pugh-matrices were used to score the generated features against the proposed customer needs, where the leading features were then combined into feasible concepts. These combinations were then screened, utilizing another Pugh-matrix, where the lowest scoring concepts were eliminated. This was done to reduce the abundance of concepts down to a more manageable amount in order to analyze and develop further. For these concepts, they were then attached to the provided hull and sterndrive and simulations were carried out at speeds 10 and 12.5 $^{m}/_{s}$.

The results showed that the team's leading concept was concept H, which was an AVP with a variable sweep system that had an airfoil cross-section. This concept performed best in terms of the most important metrics, total resistive forces and a trim angle near the determined optimum. However, concepts utilizing other features performed well regarding other metrics, and the conclusion is that for further development, combinations of these features should be analyzed at a variety of different conditions.

Sammandrag

I och med den stundande elektrifieringen inom båtbranschen uppstår problem kopplade till den för närvarande dåliga förmågan att lagra energi. För att kunna öka avstånden man kan ta sig på en laddning utan att öka storleken på batterierna behöver samtliga delar på båten optimeras ur energiperspektiv. I det här projektet undersöks olika sätt att förbättra de hydrodynamiska egenskaperna hos antiventilationsplattan, en del som ser till att ingen luft sugs ner i propellern.

Målet med projektet var att skapa samt analysera en samling nytänkande designer av antiventilationsplattor på ingenjörsmässigt vis. Detta för att kunna förse Volvo Penta med data och nytänkande idéer för framtida utvecklingsprojekt. Projektet har krävt en genomgående förståelse för planande båtar och fysiken som omger dessa, samt hur den modelleras i simuleringsmjukvara. För att skaffa sig kunskapen som krävdes började gruppen med att genomföra grundlig research, där information söktes både online och internt inom Chalmers, Penn State och Volvo Penta. Denna information användes sedan för att generera funktioner som gruppen trodde kunde användas för att uppnå målet. Funktionerna bedömdes sedan jämfört med varandra i en Pugh-matris baserat på behoven som hittats och de bästa funktionerna kombinerades för att skapa koncept. För att minska antalet koncept analyserades även dessa med hjälp av en Pugh-matris. De kvarvarande koncepten analyserades sedan i simuleringsmjukvaran *STAR-CCM+*, där de placerades på ett skrov med hastigheterna 10 och 12,5 m/s.

Resultaten visade att koncept H, med ett ”variable sweep”-system, presterade bäst sätt till det viktigaste måttet totalt motstånd. Koncept som använde andra funktioner presterade dock bra på andra fronter, och slutsatsen är att för att utveckla projektet vidare behöver de nuvarande koncepten korsbefruktas för att sedan testas vid en mängd olika förhållanden.

Acknowledgements

Throughout the duration of the project, the team has received external help from multiple sources. WThe team would like to thank everybody involved:

Thank you to supervisors Lars Almefelt, Mikael Enelund and Arash Eslamdoost, as well as examiners Ola Isaksson and Paris Vonlockette for continuously providing help, feedback and plenty of expertise. An additional thanks to the team's industry sponsor, Björn Wessman, and the Volvo Penta technical team consisting of Lennart Arvidsson, Lars Johansson, Johan Tell and Jon Wingren for helpful input and providing them with necessary geometries and data. The team would also like to thank C3SE for accommodating them with the much needed computational power of Vera.

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Emil Nilsson, Oskar Tylén, Emma Velin

Gothenburg, May 2021
State College, May 2021

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Nomenclature

Acronyms

6-DOF Six Degrees of Freedom

AHP Analytical Hierarchy Process

AVP Anti-Ventilation Plate

CAD Computer Aided Design

CFD Computational Fluid Dynamics

HPC High-Performance Computing

Variables

β Deadrise angle of the hull

ϵ Drive angle

λ Wetted length to beam ratio

ρ Density

τ Trim angle

D_{AVP} AVP drag

D_{skeg} Skeg drag

D_{spray} Spray drag

D_{strut} Strut drag

D_{torp} Torpedo drag

e Lever are for the pressure force

f Distance between shaftline and centre of gravity

ff Lever arm for R_f relative to the centre of gravity

g Acceleration due to gravity

L_m Mean wetted length

L_{torp} Torpedo lift

L_{cp} Distance between centre of pressure and the transom

LCG Longitudinal Centre of Gravity, distance measured from transom

M Bow-down moment

m Hull Mass

M_a Moment of appendages

M_f Moment of friction

M_h Moment of hull

m_{tot} Total vessel mass

N Hydrodynamic and hydrostatic pressure on hull

R Total Resistance

R_{f0} Frictional resistance at equilibrium

R_f Frictional resistance on hull

Re Reynold's number

T Propeller thrust

V Speed

VCG Vertical Centre of Gravity, distance measured from baseline (keel)

$\Delta\lambda$ Change in wetted length to beam ration

1 Introduction

With the increasing electrification within the boating industry, problems associated with existing, low energy-dense batteries arise; thus, creating the need to optimize a drive unit's efficiency. This transition has led to an extensive demand to minimize the resistance of each part used within a boat's schematic; more so, an electric powered sterndrive. This report covers an investigation into ways to optimize the hydrodynamic performance of an anti-ventilation plate, which prevents surface air from being drawn into the low pressure side of a propeller. In this case, on a future 300-kW electric powered sterndrive presented by Volvo-Penta, its combustion engine powered predecessor depicted in figure 1.1.

Figure 1.1: *Volvo Penta Aquamatic Sterndrive - DPI; 300-400 horsepower drive with the anti-ventilation plate enclosed in red [1].*

1.1 Background

In the past decade, electrification has been a hot topic within many technical industries; among them, the boating industry. In this case, one of the biggest challenges within electrification is the ability to store enough energy to be able to run motors for a substantial amount of time. The batteries used are heavy, take up a lot of space, and expel significant amounts of energy due to undesired conditions. To minimize this energy waste, all unnecessary uses of energy should be mitigated to increase the motor's functionality.

All planing boats and vessels equipped with outboard engines and sterndrives are also equipped with anti-ventilation plates (AVP). A problem arises because there are no established theoretical models for their functionality and performance where instead, most of them are based on production limitations, trials, and the legacy of previous designs. Due to the lack of existing models, it is probable that anti-ventilation plate geometries could be improved. The lack of exhaust gases from electrical drives might also provide new possibilities for how to improve the functionality of an anti-ventilation plate as environmental gases — surface air — are now the only gases that can cause ventilation of the propeller. Also, in contrast to the anti-ventilation plate on the *Aquamatic Sterndrive* in figure 1.1, the plate on an electric powered drive will not double as an exhaust pipe. This situation reduces the need for making compromises and allows more creative ideas for the design and implementation of an anti-ventilation plate. Moreover, the increased instantaneous torque of the electric motor might also increase the risk of ventilation during maneuvering.

Currently, there is no standard design of an anti-ventilation plate that is supported by literature and research. The drag of the plate itself is very low compared to the hull, and significant changes in its design will not alter this fact. However, a winglike object can create a lift force much larger than its drag; and as this is true for the AVP, it can alter the orientation, or trim, of the hull. This will have a much larger impact on the overall resistance as the trim of the hull is vital to its drag.

Also, working similarly to a wing, the hull will invoke both more hydrodynamic lift and drag, the more it trims (compared to the angle of attack on a wing). On the other hand, the higher a hull rides on the water, the lower the drag. This creates a compromise between the high and low trim and ride height. This will create different optimal trims for various speeds, as both lift and drag are proportional to the square of the speed. At very high speeds, lift will be sufficient for a high ride height meaning low drag even at low trim angles; whereas at low speeds, a higher trim is needed. If the speed is even lower such that the boat is not properly planing but in a transition between planing and displacement, another phenomena occurs. The waves pushed forward by the hull will lift the bow to create an extreme trim with a lot of drag, still the speed is insufficient for creating substantial lift, even at the extreme trim angles. This leads to a high drag and the obvious need to counter this trim. In short, anti-ventilation plates lift might be required in different directions at different speeds.

It should be noted that anti-ventilation plates are sometimes incorrectly called anti-cavitation plates. Cavitation and ventilation are different pheonomenas though, the main difference being the origin of the gas in the propeller. Cavitation occurs when there is an extreme reduction in pressure on the back side of propeller blades [2]. Pressure on the propeller's blades is reduced as the propeller's velocity increases, and if the pressure is reduced low enough, water will evaporate on the surface of the propeller. The steam bubbles causes the propeller to erode. Ventilation is caused by a reduced pressure at the low pressure side of the propeller which allows environmental air to be drawn into the system. This is because the fluid will follow the pressure gradient and go from a higher to a lower pressure. When it happens the propeller loses traction on water, thus reducing the forward thrust while the rotational speed increases. This increase in rotational speed can cause extensive cavitation [2], as well as effectively contribute to energy loss. The purpose of an anti-ventilation plate is to prevent surrounding gases from being sucked into the low-pressure side of the propeller blades, by blocking it's path, effectively preventing ventilation.

1.2 Problem Statement

Throughout the past years, anti-ventilation plate designs have been very consistent within industry. There is strong reason to believe that there could be more efficient geometries, and that supplementary functions could be performed by the AVP. For example, anti-ventilation plates could enhance performance by allowing the boat to plane sooner, reducing the overall drag on the system, but not necessarily on itself.

In modern age, electric boats are becoming more popular and feasible to manufacture. As a result, the team has been tasked to generate and analyze a number of unique and innovative anti-ventilation plate designs through impartial engineering practices which will supply Volvo with data and ideas for further consideration on future AVP development. Furthermore, companies have released solutions to counter ventilation issues, but these solutions appear to be ineffective causing AVP designs to be relatively consistent within industry. Because of this, the team was able to create the following list of objectives upon the completion of developing an anti-ventilation plate:

- Develop an anti-ventilation plate that prevents air from reaching the propellers.
- Create an anti-ventilation plate which induces low resistance to decrease the power consumption of the system.
- Look into anti-ventilation plate designs that generate forces that will positively impact the hull's trim angle.
- Consider both static and dynamic anti-ventilation plate designs.

1.3 Project Management

This project is a collaboration between Chalmers University of Technology, Pennsylvania State University, and the sponsor, Volvo Penta. Three of the students are from Chalmers, and four are from Penn State. Each week there has been two to three reoccurring meetings where all students have been present. On one of those, the team has also been joined by its supervisors. When needed, extra meetings have been scheduled. Additionally, the six hour time difference has caused no major issues.

Moreover, the team was divided into roles to increase the efficiency of completing objectives while working asynchronously. Each team member was given one of the roles they were most proficient at or most interested in learning. In addition, one team member was chosen to be the point of contact between the students and the sponsor. This management strategy allowed all students to have a clear understanding of what's going on and what future objectives needed to be accomplished. It also helped the team allocate work between team members to reduce excessive workloads on an individual.

1.4 Project Delimitations

Any limitations within the project are based off of industry regulations and the safety of the anti-ventilation plate design concept. The goal was to produce the most effective design that adheres to regulations and requirements presented by Volvo Penta. The plates were designed for planing boats of a size around ten meters in length and not capable of exceeding speeds of 17.5 $^{m}/_{s}$ (roughly 34 knots). Moreover, no other parts other than the anti-ventilation plate were considered. Another limitation presented with this project is the computational space allotted to the team for use of high-performance computing (HPC) computers [3]. Because the team were utilizing these to finalize simulations of the leading concepts and the resulting simulation files are so large, the team was limited in the amount of analyses and concepts that they were capable of running. Therefore, designs were only evaluated at two speeds in planing mode going straight, no turning, no acceleration. The ventilation mechanism was not evaluated either.

1.5 Thesis Outline

The report covers the team's developmental process of coming up with, conceptualizing, and analyzing a number of innovative designs for the iterative redesign process of an anti-ventilation plate. It is formatted in chronological order to convey the team's work process and accomplishments as events unfolded throughout the duration of the project. This impartially allows the reader to closely relate to the team's thoughts and actions and better understand their design process.

Because the projects scope revolves around such a niche area of study with complex theory and application, the succeeding chapter provides information that will supplement the reader as it aided in the team's understanding of the various, complex topics involved. The two following sections after the aforementioned consist of the team's concept generation and development phase; and discusses the various methods, software, and tutorials used to complete these phases. The ending sections involve the team's analyses of generated concepts, a discussion of the project as a whole, and a conclusion with recommendations for further development or work.

The appendices are utilized to include various figures or documents that are mentioned in the report; and although not required for the reader's understanding, supplement what the students have done. Basically, it provides the reader with more information to further understand what, how, and why something was performed by the team.

2 Background Research and Theory

In this project, the team were focusing on the innovative development of an anti-ventilation plate. For this, the team had to acquire knowledge of the plate and also the variables that effect it. To perform the simulations needed to draw conclusions about their concepts' impact on the system, the team also had to gather knowledge about how to properly use the simulation software, *STAR-CCM+* [4]. The project's background research and findings are presented within this chapter.

2.1 AVP Background Research

To understand the basics of how an anti-ventilation plate works, each group member carried out and learned supplemental information through individual research. However, due to a lack of scientific research regarding AVPs, the main sources of information were patents, and online boating forums — which were filled with the opinions and knowledge of experienced users.

The main purpose of an AVP is to prevent surface air from being sucked into the low-pressure side of a propeller [2]. There have also been attempts to extend its functionality to aiding the hydrodynamic performance of a boat [5]. However, these systems seem to be few and far between, where for the most part, the development of AVPs has been stagnant as current solutions fulfill the purpose of preventing ventilation.

For normal use, the team found that the sterndrive should be mounted at a height where the AVP is between 10 and 25 mm above the bottom of the hull. This is low enough to prevent ventilation, but not so low that it causes unnecessary losses of energy inhibiting the propeller's efficiency [6].

2.2 Physical Modeling

To better understand the physics regarding the project's scope, as well as the consequences of altering an AVP within the drive's system, a free-body diagram drawing was created. This provided a further understanding of the various forces that act on the system along with a rough estimate of the forces' magnitudes. The model, depicted in figure 2.1, is based on a combination of literature for the behaviour of planing hulls and models of forces acting on the drive unit [7][8]. Although not as accurate as say, simulations, the model supplements an understanding of certain parameters that may affect the overall resistance on the hull; such as resistance as a function of the trim angle. Moreover, the succeeding method provides means to relate empirical data obtained through simulations to values obtained through theory.

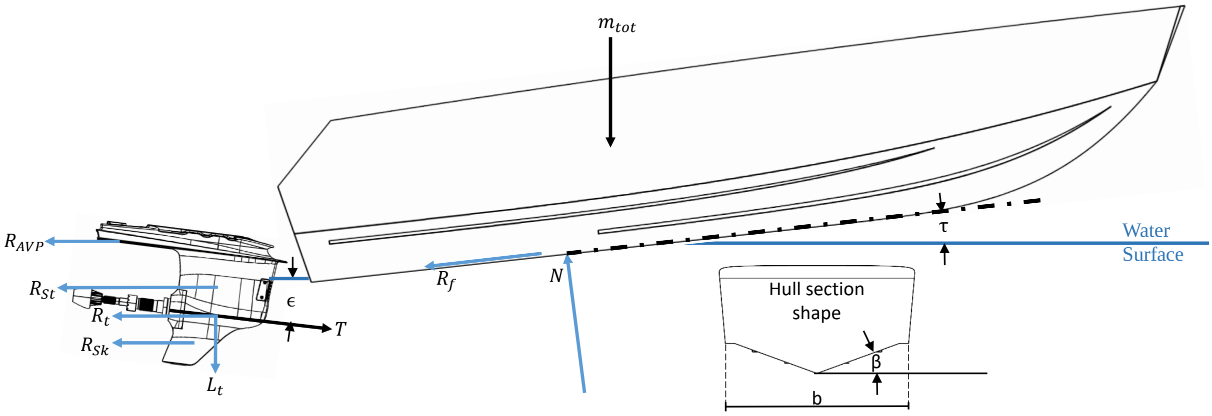


Figure 2.1: *Forces acting on hull and drive (not pictured to scale).*

2.2.1 Hull Behaviour

A method for hand calculating the equilibrium angle and the corresponding forces of a hull can be found in *Principles of Yacht Design* by Larsson et al. [7]. The method is commonly referred to as the *Savitsky* method [9][10], and was implemented in this project using the MATLAB [11] script given in Appendix A.

Step-by-Step Solution

The *Savitsky* method was implemented into MATLAB using the following procedure [7]:

1. Determine total mass m_{tot}, velocity V, and the following measurements (figure 2.1):
   - VCG
   - LCG
   - ε
   - β
   - b
   - f
2. Compute speed coefficient, C_{v}:

$$C_{\text{v}} = \frac{V}{\sqrt{gb}} \tag{2.1}$$

   where g is gravitational acceleration and b is beam length.

3. Compute flat plate theory lift coefficient, $C_{\text{L}\beta}$:

$$C_{\text{L}\beta} = \frac{m_{\text{tot}}g}{0.5\rho V^2 b^2} \tag{2.2}$$

   where ρ is the density of water.

4. Through Newton's method, iterate for the corresponding lift coefficient C_{L0} for the deadrise angle β of the chosen hull using:

$$C_{\mathrm{L}\beta} = C_{\mathrm{L0}} - 0.0065\beta C_{\mathrm{L0}}^{0.6} \tag{2.3}$$

5. Assume a trim angle τ, say 1°.

6. Through Newton's method, iterate for the wetted length to beam ratio, λ, using:

$$C_{\mathrm{L0}} = \tau^{1.1}\left(0.012\lambda^{0.5} + 0.0055\frac{\lambda^{2.5}}{C_{\mathrm{v}}^2}\right) \tag{2.4}$$

7. Compute mean wetted length, L_{m}, and Reynold's number :

$$L_{\mathrm{m}} = \lambda b \tag{2.5}$$

$$Re = \frac{VL_{\mathrm{m}}}{\nu} \tag{2.6}$$

where ν is the kinematic viscosity of water.

8. Compute skin friction coefficient, C_{f}:

$$C_{\mathrm{f}} = \frac{0.075}{(\log(Re) - 2)^2} \tag{2.7}$$

9. Find the increase in λ due to spray, $\Delta\lambda$, from figure 2.2. Calculate the friction resistance, R_{f}:

$$R_{\mathrm{f}} = C_{\mathrm{f}} \cdot 0.5\rho V^2(\lambda + \Delta\lambda)\frac{b^2}{\cos(\beta)} \tag{2.8}$$

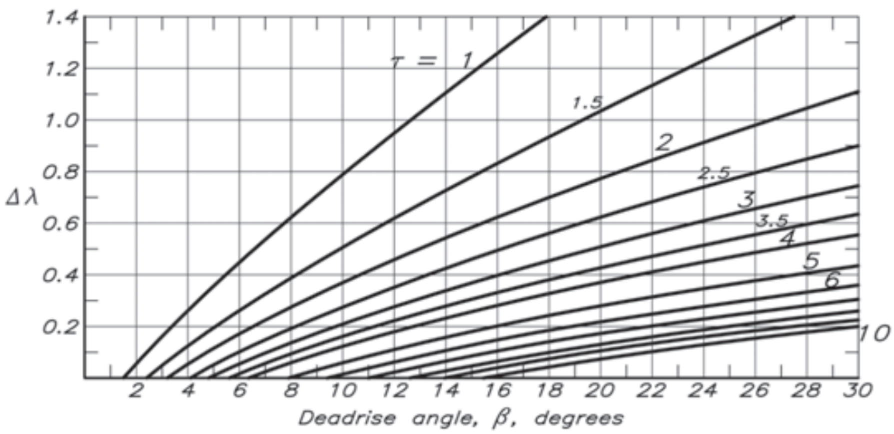


Figure 2.2: $\Delta\lambda$ *at different deadrise and trim angles [7].*

10. Compute the lever arm for R_{f} relative to the center of gravity, ff

$$ff = VCG - \frac{b}{4}\tan(\beta) \tag{2.9}$$

11. Compute the appendage resistance (for the theory used in this project, see section 2.2.2).

12. Compute the lever arms for the appendages relative to the center of gravity of the hull.

13. Compute the distance between the centre of pressure and the transom, L_{cp}:

$$L_{\mathrm{cp}} = L_{\mathrm{m}} \left(0.75 - \frac{1}{\frac{5.21 C_{\mathrm{v}}^2}{\lambda^2 + 2.39}} \right) \tag{2.10}$$

14. Compute the lever arm for the pressure force, e:

$$e = LCG - L_{\mathrm{cp}} \tag{2.11}$$

15. Compute the resulting bow-down moment, M:

$$M_{\mathrm{h}} = m g_{\mathrm{tot}} \left(\frac{e \cdot \cos(\tau + \varepsilon)}{\cos(\varepsilon)} - f \frac{\sin(\tau)}{\cos(\varepsilon)} \right) \tag{2.12}$$

$$M_{\mathrm{f}} = R_{\mathrm{f}} \left(f_{\mathrm{f}} - e \cdot \tan(\varepsilon) - \frac{f}{\cos(\varepsilon)} \right) \tag{2.13}$$

$$M_{\mathrm{a}} = R_{\mathrm{a}} \left(f_{\mathrm{a}} - e \cdot \tan(\varepsilon) - \frac{f}{\cos(\varepsilon)} \right) \tag{2.14}$$

$$M = M_{\mathrm{h}} + M_{\mathrm{f}} + M_{\mathrm{a}} \tag{2.15}$$

16. This will most likely have resulted in a negative bow-down moment. Repeat steps 5 through 15 while increasing the trim angle slightly.

17. After getting a positive bow-down moment, compute the equilibrium trim angle, τ_0, using linear interpolation between the last two values:

$$\tau_0 = \tau_1 - \frac{M_1(\tau_2 - \tau_1)}{M_2 - M_1} \tag{2.16}$$

18. Compute the frictional resistance at equilibrium, R_{f0}, by linear interpolation between the last two values:

$$R_{\mathrm{f}_0} = R_{\mathrm{f}_1} + \frac{R_{\mathrm{f}_2} - R_{\mathrm{f}_1}}{\tau_2 - \tau_1}(\tau_0 - \tau_1) \tag{2.17}$$

19. Compute the total resistance, R:

$$R = (mg \cdot \sin(\tau_0) + R_{\mathrm{f}_0}) \frac{\cos(\tau_0 + \varepsilon)}{\cos(\varepsilon)} \tag{2.18}$$

2.2.2 Forces on Drive Unit

To find the influence of an anti-ventilation plate regarding a hull's behaviour, the *Savitsky* method had to be coupled with other theoretical equations concerning forces on different parts of the drive unit. The most relevant theory found comes from work at *Mercury Marine* and the report in question presents ways to calculate the forces on different parts of the sterndrive; which include the anti-ventilation plate, strut, torpedo, and skeg [8]. This allowed the team to understand and consider the various forces that would be present upon simulations of the sterndrive as a whole. Moreover, it allowed the team to quantify values that could be incorporated into the aforementioned *Savitsky* method to provide values for future comparison.

- **Lift Force**
  The only lift force on the drive unit is acting on the torpedo and can be calculated as follows:
  $$L_{\text{torp}} = 0.030\varepsilon\frac{1}{2}\rho V^2 d^2 \tag{2.19}$$
  It was initially thought, and desired, that the anti-ventilation plate were to provide lift to the drive in order to aid in planing. However, as it will also be discussed later, this proved to be wrong as the AVP could actually aid in the planing of a hull by influencing the trim, and thereby lift and resistance, of the hull altogether. With that being said, this lift force could possibly contribute to this effect as well.

- **Drag Force**
  Drag forces include resistive forces generated from various parts on the sterndrive which consist of the sterndrive's strut, skeg, torpedo, and AVP. These forces can be calculated as follows:
  $$D_{\text{strut}} = \frac{1}{2}\rho V^2 C_{\text{D}_{\text{strut}}} A_{\text{strut}} \tag{2.20}$$
  $$D_{\text{skeg}} = \frac{1}{2}\rho V^2 C_{\text{D}_{\text{skeg}}} A_{\text{skeg}} \tag{2.21}$$
  $$D_{\text{torp}} = \frac{1}{2}\rho V^2 C_{\text{D}_{\text{torp}}} \frac{\pi d^2}{4} \tag{2.22}$$
  $$D_{\text{spray}} = \frac{1}{2}\rho V^2 (0.011tc + 0.08t^2) \tag{2.23}$$
  $$D_{\text{AVP}} = \frac{1}{2}\rho V^2 C_f A_{\text{AVP}} \tag{2.24}$$
  It is worth mentioning the omitted equation – equation 2.24 – that causes an additional resistive force, and that is the force generated due to spray from the strut. It will be discussed in future content but it's interesting acknowledging the equation and its direct correlation to the planform, or wetted surface area of the plate.

2.3 CFD Tutorials

Although most of the group members had some basic experience with CFD simulations within STAR-CCM+, the simulations that had to be carried out in this project were far more advanced than what anyone had done before. To resolve this issue, CFD supervisor, Arash Eslamdoost, provided the team with tutorials to go through in order to understand how the simulations had to be set up. These were all from the extensive STAR-CCM+ help section and are available with a STAR-CCM+ license. The three tutorials were:

- **Taxi Boat:** Simulation of a Taxi Boat using 6-DOF model.
  A simulation of a planing hull model at 3.5 m/s. This tutorial was closest to what

the team was going to do for their concepts; however, it was slightly outdated and required an up-to-date tutorial on generating a mesh.

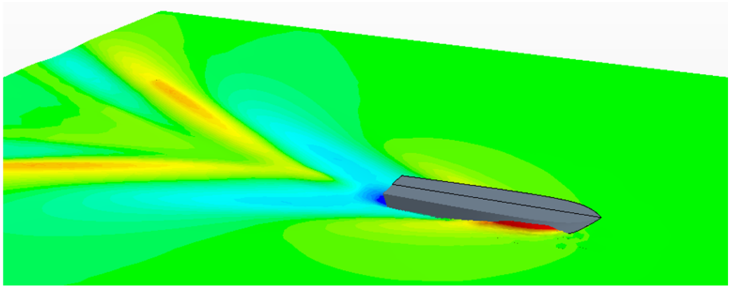


Figure 2.3: *Free surface resulting from the taxi boat tutorial.*

- **Marine Resistance Prediction; KCS Hull with a Rudder:** A simulation of a displacement hull using the up-to-date meshing method.
- **Body Force Propeller Method:** Another version of the simulation above, this time implementing a virtual disc model to simulate the impact a propeller would have on the flow and hull.

In addition to the tutorials, the CFD-supervisor provided the team with plenty of assistance throughout the analyses described in section 5.

3 Concept Generation Methodology

Upon identifying the problem statement and learning about the project's scope, the team began the concept generation phase. This was done in order to begin providing innovative and unique solutions to the prescribed task and ended up being an iterative process. The team began by creating a functional decomposition of the system, along with identifying a black-box diagram of the various parameters that influenced the system. They progressed to idea generation which would then supplement the team with proposed concepts. The concepts were broken down into the sub-functions of the system, where individual Pugh-matrices were made and the corresponding ideas were objectively scored against each other. These leading sub-functions were then combined utilizing a concept combination table, scored using another Pugh-matrix, which then allowed the team to begin development of the resulting, leading concepts.

3.1 Function Structure

To make sure that the developed concepts fulfilled the customer needs, a functional decomposition was used to break the concepts functionality down into relevant categories. The resulting functions and sub-functions identified were used to generate and evaluate concepts created in the concept generation and refinement phase. Furthermore, the team also developed a black-box diagram to supplement their understanding regarding the functionality of the system, along with some of the proposed sub-systems.

3.1.1 Black-Box Diagram

A black box diagram is an engineering tool used to specify inputs and outputs to further understand and analyze a system. The resulting black-box diagram of an anti-ventilation plate for Volvo-Penta's Aquamatic DPI Sterndrive is depicted within figure 3.1. Initially, the main sections for the output of the anti-ventilation plate included counteracting ventilation, generating lift force, and adaptation to high-speeds. From the prescribed customer needs, it was found that the desirable functions would be these aforementioned results. Primarily, the AVP should prevent ventilation as best as it could. It was found that there's potential that the plate could contribute to lift force which would benefit the boat's functionality and aid in its planing. And finally, the ability for the anti-ventilation plate to adapt and remain functional while at high speeds was another desired outcome.

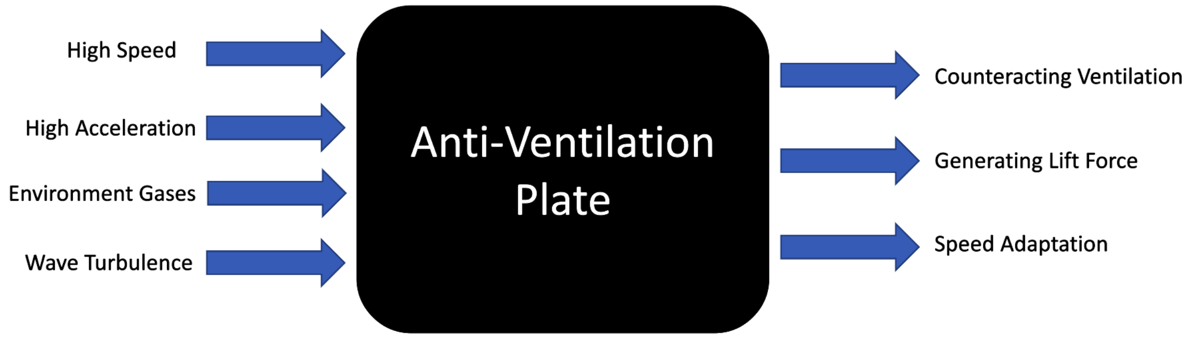


Figure 3.1: *The team's resulting black-box diagram upon identifying various parameters of the system.*

The team initially found that the main parameters that involved counteracting ventilation included high speed and acceleration, surrounding environmental gases (like air), and the magnitude of the surrounding waves' turbulence. Although true, the team initially neglected overall resistance along with the initial trim angle; two parameters that the team spent some time optimizing for computational fluid dynamic (CFD) analyses. Nonetheless, increased speeds and accelerations create huge pressure differences between the low pressure side of the propeller and the water and air above it. These pressure differences create suction for air, or environmental gases, to be drawn into the propeller which inhibits its functionality and may cause ventilation. And then there is wave turbulence where, depending on the severity of the magnitude, the AVP may fail to be submerged at times. This would bring air into the system and again, affecting the propeller's functionality.

3.1.2 Functional Decomposition of the Anti-ventilation plate

With a black-box diagram constructed, it was then broken down into various sub-functions to understand how the inputs within the diagram become outputs of the system; this is called a functional decomposition and is depicted in figure 3.2. By doing it this way, it allowed the team to supplement the knowledge of the system and the overall function can be studied and decomposed into auxiliary functions. These, along with the corresponding sub-functions, were used to investigate or resolve the initial problem statement.

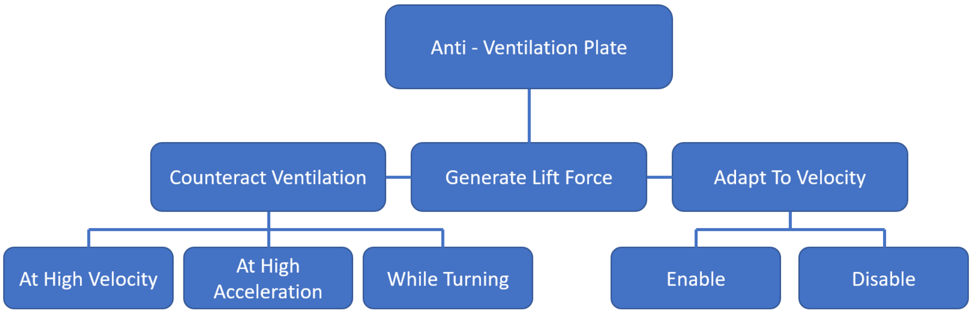


Figure 3.2: *A functional decomposition which breaks down the parameters expressed within the black-box diagram.*

In figure 3.2, the system should be able to counteract ventilation while operating at high velocities and accelerations, and also while turning. The ability to adapt to velocity should also have the option to be enabled or disabled at different times – the result of a dynamic request. And finally, the system, or plate, should be able to produce lift. The team believed that with these functions in mind, an adequate anti-ventilation plate could be generated during development.

3.2 Costumer Needs and Specifications

Through the research and input from Volvo Penta, the customer needs and specifications could be determined. The customer needs were specified to produce a more efficient and innovative design for an anti-ventilation plate on Volvo Penta's *Aquamatic Sterndrive - DPI*. The determined customer needs and specifications were compiled into a customer needs-metrics matrix which allowed the team to qualitatively observe how certain needs corresponded to various metrics. This matrix can be examined in table 3.1.

Table 3.1: *Customer needs-metrics matrix with initial determined parameters.*

Anti-Ventilation Plate Customer Needs Chalmers, PSU									
	Metric								
Customer Needs	Angle of Attack	Drag Coefficient	Lifespan	Lift Coefficent	Planform Area	Longitudinal Position	Vertical Position	Thickness	Trailing Edge Radius
Assist Transition from Displacement to Planing	High	Low		High	Large	Requires CFD	Requires CFD		Small
Dampen Gearwhine and Propeller Noise									
Durability			Long					Thick	Large
Ecological Sustainability		Low	Long		Small			Requires LCA	Requires LCA
Fast Appearance						Further Back		Thin	Sub 1.5mm
Functionality up to 17.5 m/s	Low	Low		Negative		Requires CFD	Requires CFD		
High-Thrust Manouvering Functionality					Large	Further Back	High		
Low Drag	Low	Low			Small	Further Forwards	High	Thin	Sub 1.5mm
Prevent Splash	Requires CFD				Large	Requires CFD	High		
Resisitive to Significant Pressure Differences			Long	Low	Small	Middle		Thick	
Retain Functionality While Turning	High				Large	Requires CFD	Requires CFD		
Target Specifications									1.5 mm
Maximum	-15°								1.5 mm
Minimum	0°								1.5 mm

When looking at the needs-metrics matrix, it can be coherently read by *"-customer need- is satisfied when -corresponding metric- (highlighted) is sufficiently -internal text-."* For example, relating the customer need and metric in column one, row one reads: *"Assist transition from displacement to planing is satisfied when the angle of attack is sufficiently high."* Similarly, other customer needs and their corresponding metrics can be read the same way.

It should be noted that this matrix lacks target specification which is attributed to the lack of data found during initial discussion and research. The team wanted to wait until analyses on the provided AVP were performed in order to obtain these values. Furthermore, the customer needs changed in order to simplify analyses and be tailored to what was actually being recorded from these simulations. This topic and the resulting parameters are discussed in a later section.

Although the project is sponsored by Volvo Penta, the information and results within are limited and can be used or implemented into others' designs. The team hopes to add value and research to this niche area of study that will further supplement future designs.

3.3 Idea Generation

Upon identifying the function structure, the team began to consider ideas that would influence and help build eventual concepts for the group. The idea generation process included two main techniques in order to efficiently generate effective concepts based on the prescribed problem statement and customer needs. These two methods include *Brainswarming* [12] and Method 6-3-5, which is also known as *Brainwriting.* [13]

Brainswarming is a concept generation technique created by the cognitive psychologist, Tony McCaffrey. Rather than coming up with ideas within a group setting, this technique utilizes an individual's own time to add ideas with sticky notes to an ever-changing "map" where the problem statement is listed at the top and the resources are listed at the bottom. This creates a dynamic environment for ideas to flourish and grow by allowing someone to work top-down, bottom-up, and even off of other's ideas [12]. This technique allows individuals to submit ideas anonymously and judgement-free; isn't limited to a single meeting but instead has a designated time frame; and isn't hindered by the time differences presented within this group.

Brainwriting (6-3-5 Method) presents another efficient way to come up with ideas for solutions to the presented problem. In this method, there are six people that should come up with three ideas within a five-minute time period, hence 3-6-5. Once the five minutes are up, the paper in which the ideas are on is then passed to the left where the next person builds off of the previous person's three ideas, again, within five minutes. This is done until everyone has seen each individual's paper. By the end of the session, a magnitude of ideas should be generated. The group can then discuss, refine, clarify, and build off of the ideas generated [13]. To note, although its recommended use is six people, this can be completed with a minimum of four and maximum of eight people.

Due to the volume of generated ideas, the team decided to visualize the member's individual ideas through illustrations shown in figure 3.3. They believed that in doing so, it would aid in conceptualizing some of the abstract ideas while also being able to communicate one's ideas to another. This was important because during the brainstorming sessions, abstract and unconventional ideas were encouraged as it would add variety and uniqueness to the array of concepts.

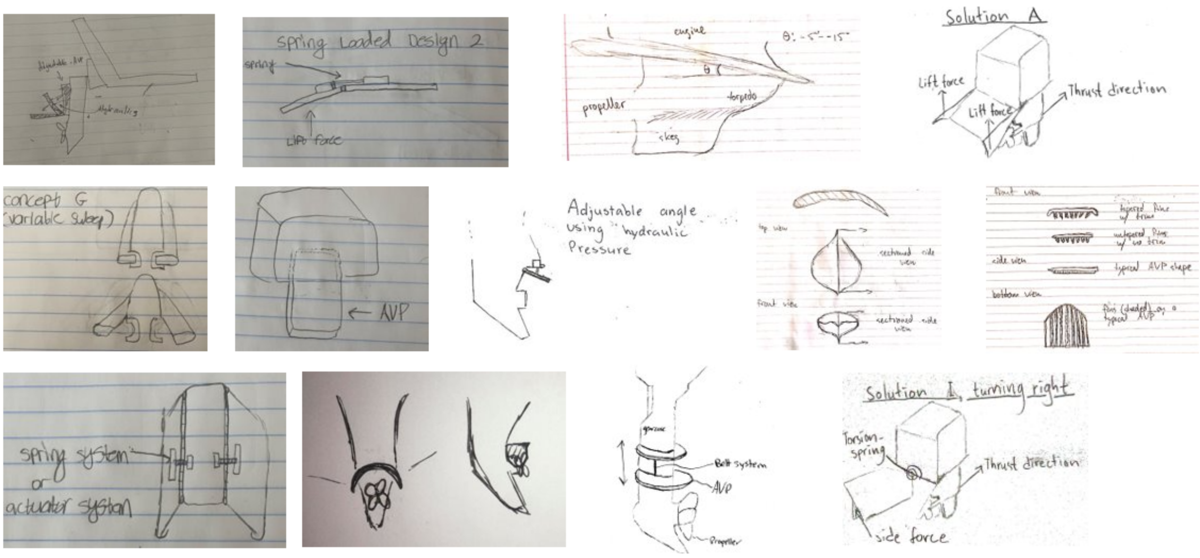


Figure 3.3: *Some initial ideas regarding various aspects of an AVP.*

In figure 3.3, the team's first ideas are presented to get a visual perspective of some of the proposed concepts. There sketches include various concepts and ideas that would later be implemented into a number of the team's designs. .

3.4 Concept Screening

Once a substantial amount of ideas were generated, the team constructed a Pugh-matrix utilizing the determined customer needs with the identified metrics. However, upon attempting this, they believed that the concepts should be further broken down in order to compare the ideas objectively as some contributed to the needs more than others. The team believed this to be an unfair comparison and further decomposed the functions into sub-functions.

These comparisons made within the Pugh-matrices are in reference to features on Volvo Penta's current anti-ventilation plate and were compared using fundamental analysis. This iterative process ensured that the features within the sub-functions and combined matrices were compared objectively. This allowed some concepts to distinguish themselves over others and clarified which concepts were to be explored further and which ones were to be ignored. However, if one of the bad concepts seemed to be performing very well in one particular metric, there were a good reason to try and figure out a way to incorporate this concept into a preexisting one that might be performing poorly within the same metric. This create potential to lead to a new concept which may out-perform one of the originals. Any concept that was eliminated along the way were still in the matrices, showing why it was not chosen. This refinement was important due to the requirement of extensive analysis of the hydrodynamic performance of the leading concepts in order to attain valid, quantitative values to supplement the choice of a unique design further down the line.

3.4.1 Decomposition of Functions

The team believed it to be important to decompose the features of the anti-ventilation plate due to the various and unique features that were hard to compare within the original

Pugh-matrices. They believed that some features scored better against others and that there seemed to be redundant themes across a couple of the designs. The features that a large amount of the sub-features could fall under included: a unique feature on an AVP; the shape of an AVP; and whether the plate would be static or dynamic. Because of this, the team wanted to objectively compare similar features against each other which would limit the amount of outliers that would appear throughout the concepts. They would then be able to take the leading ideas from each matrix, combine them with an analytical approach, then compare them against each other within another matrix.

3.4.1.1 Features Sub-Function Scored in a Pugh Matrix

The *features* sub-function scoring consisted of features that could be unique to an anti-ventilation plate in the sense that it may add possible benefits that the *shapes* or *static versus dynamic* sub-functions could not. Regarding an AVP and the ideas the team came up with, the features include, but are not limited to: fins applied to the underside of a plate; trimmed, outer edges of the plate; and an angled sterndrive to promote planing quicker rather than trimming the sterndrive itself. The others can be read in the right side of table 3.2.

Table 3.2: *Pugh-matrix for features sub-function.*

Pugh-matrix										
Chalmers, PSU	Reference: Plain plate with no features									
	Solution									
Function	A	B	C	D	E	F	G	H	I	Ref
Counteract ventilation	0	0	0	0	0	0	0	0	0	0
Counteract ventilation while turning	+	0	0	0	0	0	+	0	0	0
Dampen Noise	+	-	-	0	0	+	0	0	0	0
Durability	+	0	0	+	0	+	-	-	-	0
Fast Appearance	+	-	+	0	+	+	0	0	0	0
Generate lift force	+	0	0	0	+	0	0	+	+	0
Limit drag force	0	+	+	+	+	+	+	+	+	0
Prevent Splash	0	-	-	0	0	+	0	0	0	0
Σ+	5	1	2	2	3	5	2	2	2	0
Σ-	0	3	2	0	0	0	1	1	1	0
Net Score	5	-2	0	2	3	5	1	1	1	0
Rank	1	10	8	4	3	1	5	5	5	8
Continue	Yes	No	No	Yes	Yes	Yes	No	No	No	Yes

Pugh-matrix	
Solution	Explanation
Reference	Plain, plate with no features
A	Winglets on the plate
B	Holes on the top surface of the plate
C	Holes on the top surface of the plate, with a thin layer over the hole to direct bubbles
D	Low friction/hydrophobic coating applied on plate's surface
E	Angled plate to push stern down instead of trimming drive up
F	Fins applied on bottom surface of the plate close to the propeller
G	Plate pivots horizontally - dynamic
H	Plate pivots vertically - dynamic
I	Plate moves vertically - dynamic

Static features can be incorporated into a dynamic plate system but dynamic features cannot be incorporated into a static plate system. Also, features can be combined. Moreover, features can be combined.

The reference was the standard plate that Volvo provided to the team, with the exception of removing the exhaust portion as it was no longer necessary for an electric motor. Also, the designs that the team followed through with are denoted as *yes* and were implemented into concepts within the concept combination table. Notice how the dynamic plates scored poorly in comparison to the others; one of the reasons the team wanted to decompose the original ideas initially.

3.4.1.2 Shape Sub-Function Scored in a Pugh Matrix

The *shape* sub-function is unique in that within its scoring, it compared two different types of areas; cross-sectional areas along with planform or wetted surface area. This allowed a number of unique designs, and even encouraged such ideas to be mixed and matched. Although a small amount of shapes were suggested, a couple of them include a tear drop shaped planform area, an airfoil cross-sectional area, and curved cross-sectional area. The remainder of the ideas are shown on the right side of table 3.3.

Table 3.3: *Pugh-matrix for shape sub-function.*

Pugh-matrix							
Chalmers, PSU	Reference: Typical, rectangular plate						
	Solution						
Function	A	B	C	D	E	F	Ref
Counteract ventilation	0	0	+	0	0	+	0
Counteract ventilation while turning	0	0	+	0	0	+	0
Dampen Noise	0	0	+	0	0	+	0
Durability	0	0	0	-	0	0	0
Fast Appearance	+	+	-	+	+	-	0
Generate lift force	+	0	-	0	0	-	0
Limit drag force	+	+	-	+	+	-	0
Prevent Splash	0	+	+	0	0	+	0
Σ+	3	3	4	2	1	4	0
Σ-	0	0	3	1	0	3	0
Net Score	3	3	1	1	1	1	0
Rank	1	1	3	3	3	3	7
Continue	Yes	Yes	Yes	Yes	Yes	Yes	1

Pugh-matrix	
Solution	Explanation
Reference	Typical, rectangular plate
A	Airfoil-esque shape - cross section
B	Teardrop shaped plate - planform
C	Curved plate around the propeller, not aggressively - cross section
D	Plate with trimmed edges - cross section
E	Triangular shaped plate - planform
F	Wrapped plate around the propeller, aggressively - cross section

Combination of planform and cross-sectional shapes. So there is potential to combine the two to make a new shape. For instance, a rectangular shaped airfoil versus a teardrop shaped airfoil, where one may curve and the other doesn't.

Again, the comparison was in reference to the shape of the provided plate in both portrayals of areas. As you can see, all the shapes scored well so the team decided to incorporate such shapes into the combination of the results; however, split them up as two separate categories where one may be omitted and the other may not, and such.

3.4.1.3 Static Versus Dynamic Sub-Function Scored in a Pugh Matrix

The *static versus dynamic* sub-function scoring is a comparison of varying plate types and whether they are static or dynamic. This matrix is used to objectively see if the dynamic sub-functions are able to perform better than the static counterpart. This matrix is shown in table 3.4, where the team's ideas are depicted to the right side of the table.

Table 3.4: *Pugh-matrix for static versus dynamic sub-function.*

Pugh-matrix										
Chalmers, PSU	Reference: Static plate									
	Solution									
Function	A	B	C	D	E	F	G	H	I	Ref
Counteract ventilation	0	0	0	0	0	0	0	0	0	0
Counteract ventilation while turning	0	0	0	+	+	0	0	+	0	0
Dampen Noise	0	0	0	0	0	0	0	0	0	0
Durability	-	-	-	-	-	-	-	-	-	0
Fast Appearance	+	0	0	0	0	0	0	0	0	0
Generate lift force	0	+	+	0	0	0	0	0	-	0
Limit drag force	+	0	+	0	0	+	+	0	+	0
Prevent Splash	0	-	-	0	0	-	-	0	-	0
Σ+	2	1	2	1	1	1	1	1	1	0
Σ-	1	2	2	1	1	2	2	1	3	0
Net Score	1	-1	0	0	0	-1	-1	0	-2	0
Rank	1	7	2	2	2	7	7	2	10	2
Continue	Yes	No	Yes	Yes	Yes	No	No	Yes	No	Yes

Pugh-matrix	
Solution	Explanation
Reference	Static plate
A	Variable sweep
B	Pivots vertically - actuator
C	Pivots vertically - hydraulic cylinder
D	Pivots horizontally - actuator
E	Pivots horizontally - hydraulic cylinder
F	Moves vertically - actuator
G	Moves vertically - hydraulic cylinder
H*	Pivots horizontally - torsion spring+side force
I	Wings fold up, leaving spray trail

H*	Moving with use of springs by utilizing side forces.

The Pugh scoring resulted in five dynamic sub-functions estimated to perform on an equal level, or potentially better, than the static plate. However, this also determined four dynamic sub-functions that would not work as well as the reference, so these sub-functions would not be considered further within the report. Moreover, while some of the dynamic actions are the same, at the time the team believed it possible to incorporate various mechanisms that would allow for these movements but would later change this to simplify simulations.

3.4.2 Concept Combination and Scoring in a Pugh Matrix

After scoring the features, shapes, and varying plate types against each other, the team moved ahead with the leading concepts based on their respective scores. These sub-function concepts were then combined utilizing a concept combination table in order to come up with a number of unique solutions, different to what was previously conceptualized. These concepts are presented in table 3.5.

Table 3.5: *Concept combination table.*

Concept Combination Tables Chalmers, PSU				
	Criteria			
Concepts	Features	Cross-Section Shape	Planform Area Shape	Static vs. Dynamic
Concept 1	B1	A2	A3	A4
Concept 2	D1	C2	B3	A4
Concept 3	C1	C2	C3	A4
Concept 4	B1	B2	C3	A4
Concept 5	D1	B2	A3	A4
Concept 6	A1	B2	B3	D4
Concept 7	C1	C2	C3	C4
Concept 8	B1	A2	B3	C4
Concept 9	B1	B2	A3	C4
Concept 10	A1	A2	C3	C4
Concept 11	A1	A2	B3	B4
Concept 12	A1	C2	B3	B4
Concept 13	B1	A2	A3	D4
Concept 14	B1	B2	B3	D4
Concept 15	B1	D2	C3	D4
Concept 16	A1	D2	A3	D4
Concept 17	A1	D2	B3	D4
Concept 18	A1	D2	C3	D4

Features	
A1	Winglets on the plate
B1	Slip repellant surface throughout the plate
C1	Angled plate to push stern down instead of trimming drive up
D1	Fins applied on bottom surface of the plate close to the propeller
Cross-Sectional Area - Shape	
A2	Airfoil-esque shape - cross section
B2	Curved plate around the propeller, not aggressively - cross section
C2	Plate with trimmed edges - cross section
D2	Wrapped plate around the propeller, aggressively - cross section
Planform Area - Shape	
A3	Teardrop shaped plate - planform area
B3	Triangular shaped plate - planform area
C3	Typical, rectangular-esque shaped plate - planform area
Static vs. Dynamic	
A4	Static plate
B4	Variable sweep
C4	Pivots vertically - hydraulic cylinder
D4	Pivots horizontally - actuator/hydraulic cylinder/torsional spring and force

From this, the team obtained eighteen different concepts. To allow easier integration of the concepts, the varying sub-functions were assigned a letter and a number. Within the table, the matrix to the left represents the combined concepts whereas the matrix to the right define the variables used for combinations. It should be noted that during this process, concept combinations could include just one feature, omit a feature, or even combine two or more of the same feature regarding the various sub-functions. However, to keep things simplistic, this wasn't done.

When the team determined their combined concepts, they were then scored within a Pugh-matrix to refine some of the proposed concepts and scoring them against the reference. The reference for the combined concepts was Volvo Penta's anti-ventilation plate as a whole, which is currently in use. The corresponding Pugh-matrix is represented within table 3.6.

Table 3.6: *Pugh-matrix for the combined concepts.*

Pugh-matrix																			
Chalmers, PSU	Reference: Current Anti-Ventilation Plate DPI Model - Electric Motor																		
	Concept																		
Function	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Ref
Counteract ventilation	0	+	0	+	+	+	0	0	+	0	0	0	0	+	+	+	+	+	0
Counteract ventilation while turning	0	0	0	+	+	+	0	0	+	0	0	+	0	+	+	+	+	+	0
Dampen Noise	0	0	0	-	-	-	0	0	-	0	0	-	0	-	-	-	-	-	0
Durability	+	0	0	-	-	-	-	-	-	-	-	-	-	-	-	0	-	0	0
Fast Appearance	+	+	+	0	+	+	+	+	+	+	+	+	+	+	-	-	-	-	0
Generate lift force	+	0	+	-	-	-	+	+	0	+	+	0	+	-	-	-	0	-	0
Limit drag force	+	-	0	-	-	0	+	+	0	+	+	0	+	0	-	-	+	-	0
Prevent Splash	-	0	-	+	+	0	0	0	+	0	0	+	-	+	-	-	-	-	0
Σ+	4	2	2	3	4	3	3	3	4	3	3	3	3	4	2	2	3	2	0
Σ-	1	1	1	4	4	3	1	1	2	1	1	2	2	3	6	5	4	5	0
Net Score	3	1	1	-1	0	0	2	2	2	2	2	1	1	1	-4	-3	-1	-3	0
Rank	1	7	7	15	12	12	2	2	2	2	2	7	7	7	19	17	15	17	12
Continue	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No

Here, the generated concepts scored are presented and the team chose to move forward with the concepts that scored a positive value. In doing so, they were able to eliminate seven concepts that were determined to be of lower ranking. Moreover, the reference would still be used for comparison of values and data obtained from CFD analyses. The team considered this to be important in order to quantify outlying target specifications and have a reference data that hopefully their concepts can best or improve upon. From this point on, remaining concepts 1, 2, 3, 7, 8, 9, 10, 11, 12, 13 and 14 were instead labeled A, B, C, D, E, F, G, H, I, J and K. Later on, an additional concept, Concept L was added. It was one of the teams supervisors ideas and will be analysed in the following chapters.

3.5 Kesselring matrix

The project was initially supposed to do a further elimination step which included a Kesselring matrix. The team made an analytic hierarchy process (AHP) matrix to valuate the costumer needs against each other to see the functions value of importance and quantify weighted scores for the needs. This was supposed to be used further within the Kesselring matrix; however, the team decided to consider this further due to the project's uncertainty in the simulations and the resulting values. In addition, the earlier identified parameters within the Kesselring matrix, like noise level and splash, were known.

This also changes what end result the project delivers, to a concept, prioritised almost exclusively on minimising resistance, as opposed to considering numerous other criteria.

4 Development and Refinement of Concepts

Once the concepts had been generated utilizing the concept combination table, the team determined which concepts were suitable to be made into three-dimensional (3D) models. Some of the concepts were either not feasible or too similar to one another, therefore, they had been ruled out before time had been spent on making a 3D model. The team then made computer-aided design (CAD) drawings on various 3D CAD software – SolidWorks or CATIA V5 – that were evaluated by professors and advisors. Using this feedback, the concepts had to be refined for later use within CFD analysis.

4.1 CAD Modeling Using SolidWorks

The primary software used was *SolidWorks* [14]. In this section the different models are presented as well as the refinements of the concepts.

4.1.1 Modeled Static Plates

The team had generated and modeled a set of static AVPs that had made it through the rigorous selection process. These designs are a combination of different shapes including a triangular shape, rectangular shape, or a teardrop shape. The use of winglets and fins theoretically generate lift and reduce drag, so a combination of both are included in some of the designs. The cross-sectional shape may either be flat or airfoil shaped, where the airfoil shape should generate lift to allow the hull to begin planing more quickly. The results of theoretical calculations of lift and drag were later compared with those obtained through computational fluid dynamics. See figure 4.1 for detailed CAD drawings displaying these features, where renderings of the final concepts may be found in Appendix B.

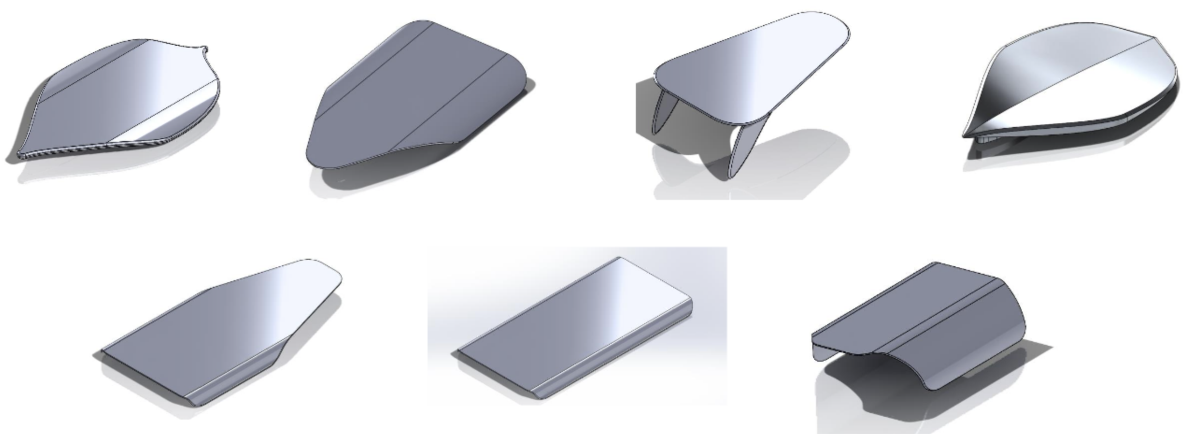


Figure 4.1: *Static plate CAD drawings with varying shapes – cross-sectional and planform area – and features.*

4.1.2 Modeled Dynamic Plates

Volvo Penta had challenged the team to consider a dynamic AVP. While this leaves more room for mechanical failure, the dynamic designs were expected to reduce drag. Some dynamic AVPs are designed to expand the planform area while the boat is transitioning from displacement to planing, then reduce the planform area while the boat is planing. The planform area is the wetted surface area which increases drag and lift, while also preventing ventilation. The other dynamic designs change the trim angle, where the AVP can tilt down towards the water to generate lift. The more lift generated, the faster the boat can reach planing. When the boat is planing, is has considerably less hydrodynamic forces acting upon the hull, therefore less thrust will be required. Minimizing the required thrust will allow battery life to be conserved so the customers can use their boat longer. Detailed CAD drawings may be seen below in figure 4.2, while renderings of finalized concepts may be similarly found in Appendix B.

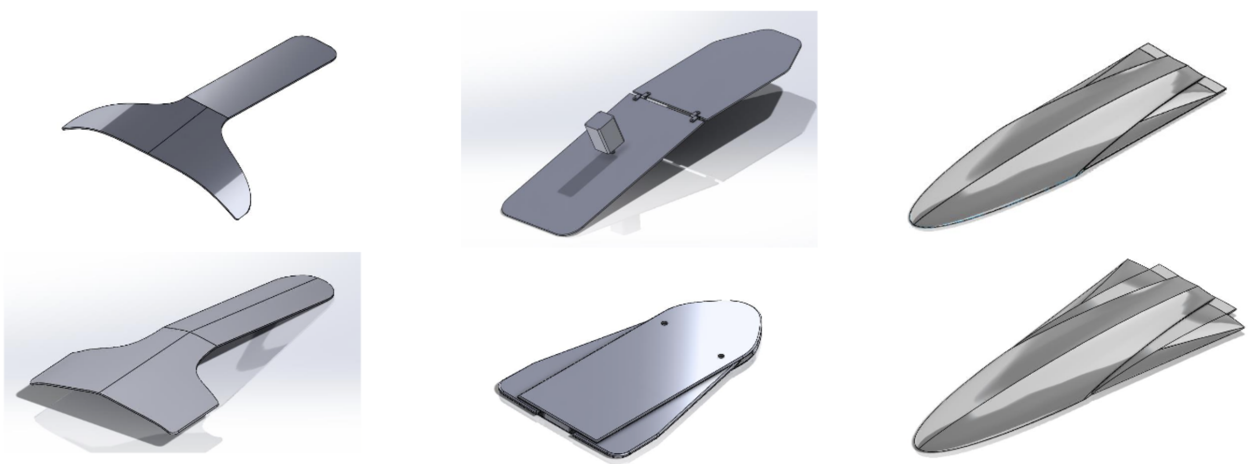


Figure 4.2: *Dynamic plate CAD drawings with varying shapes and features that allot the plate to adapt to certain conditions.*

4.1.3 Concept Refinement within SolidWorks

The process of concept refinement had been done by taking aspects of the previous concepts that were beneficial and ignoring the parts that did not work. Improving the concepts' weaknesses from the design matrix can improve a concept for further development and design. A significant influence on the final design considered the customer needs-metrics matrix and analyses regarding the outstanding needs from Volvo Penta. Further improvements regarding the team's concepts were made by adhering to their supervisors' recommendations and making the corresponding improvements. Once the team was comfortable with their designs, the drawings were made into renderings – utilizing 1060 aluminum with a cast, satin finish – to get an idea of what the AVP would physically look like. Moreover, the team would have liked to create physical models of their AVP designs, but due to COVID-19 limitations, renderings were created to in lieu of this limitation .

4.2 CFD Adjustments of CAD models

To further analyse the finished CAD models within the CFD software, *StarCCM+*, concept geometries had to be imported and simplifications of the surfacing had to be made. In this chapter, there is a walk-through on how the team implemented their CAD models within the CFD software.

4.2.1 CAD Simplification for Implementation into STAR-CCM+

After modeling the concepts in a CAD software package, the team had trouble using the created CAD models within *STAR-CCM+*. The problem was that the anti-ventilation plates and stern drive were too complex and detailed to conduct an effective simulation on. With guidance from the CFD advisor, all unnecessary details were removed from each model, essentially leaving just the outside surfaces of the system. These simplifications were made with caution to ensure it would not have a negative impact on the results of the simulation later on.

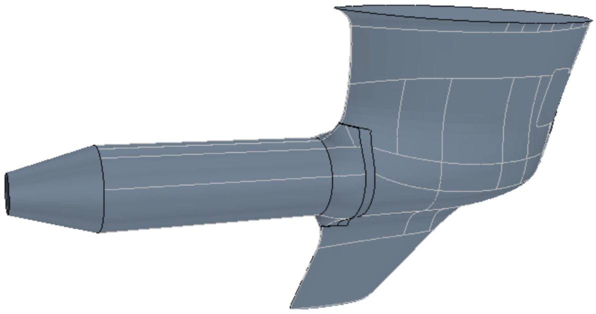


Figure 4.3: *CFD model of the sterndrive.*

The stern-drive that is seen in figure 4.3 is used in the simulations and is a refinement of Volvo Penta's original sterndrive. This is used for all the concepts to make sure they are all analysed under equal conditions.

4.2.2 Surface Simplification for CFD Analyses within STAR-CCM+

Computational fluid dynamics (CFD) was used to test and analyze the concepts to determine the resistive forces acting on the boat. Although the team would ideally run a simulation on all of the concepts, computational time is a limiting factor. If a certain design feature is proving to be the source of high resistance values, the rest of the concepts with that design feature will not be prioritized. Also, concepts where very similar features to that of another were prioritized; and if time allotted, the delayed concept would then be simulated.

Although the concepts won't be physically tested, these software analyses will provide a sufficient amount of information and data that will prove to be dependable when iterating the design process. Moreover, they will also provide an accurate look into the theory behind how an anti-ventilation plate works and prove beneficial for the possible design of other sterndrive components.

4.3 Final Design

The final design is a collection of the best AVP concepts that have the lowest values of resistance while also capable to generate the most lift. Although the final designs will not be made as a physical prototype, there are CAD renderings and schematics to display each design in Appendix B. The airfoil shaped, variable sweep, dynamic AVP had the lowest resistive values at 12.5 m/s – the concluded velocity upon iterative tests discussed in later sections. .

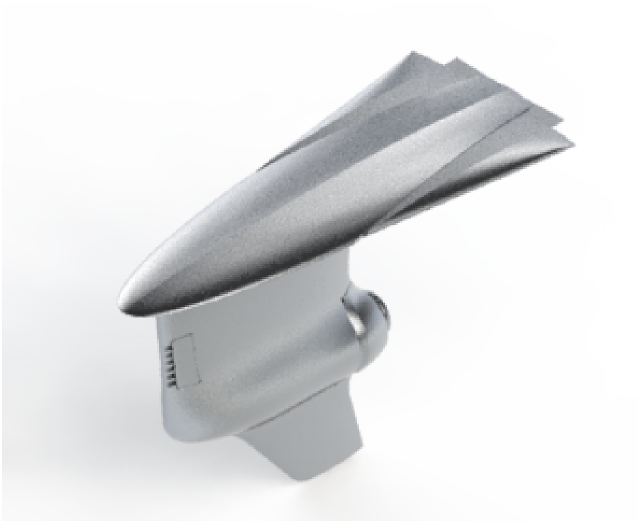


Figure 4.4: *The concept depicted is the airfoil variable, sweep, dynamic AVP. It is the leading performer when being operated under optimum conditions.*

5 Analyses of Leading Concepts

For the concepts remaining after the Pugh-matrices, further analyses had to be carried out in order to quantify metrics to be used for objective evaluation. This mainly consisted of CFD simulations.

5.1 Computational Fluid Dynamics

To evaluate the impact that concepts have on the performance of the boat, CFD simulations were run to analyse the flow around the full system of the boat. Because of its ability to model the free surface between air and water, Siemen's STAR-CCM+ was the software of choice. As the demand for computational power is quite large, the final simulations were run using Chalmer's HPC computer, Vera [3].

5.1.1 Simulation Setup in Star-CCM+

The simulations were set up based on the Siemen's tutorials mentioned in section 2. This led to the physical models in figure 5.1 being used for each concept simulation. It should be noted that for the simulations carried out in section 5.1.2.1, the virtual disc model was not enabled.

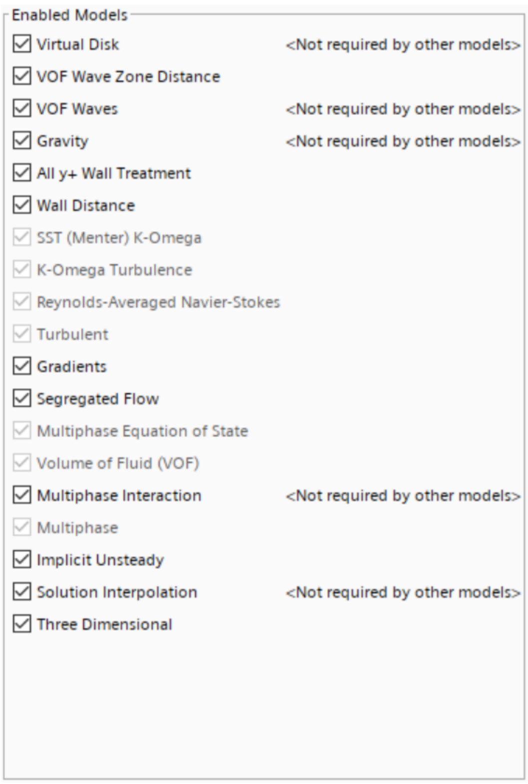


Figure 5.1: *STAR-CCM+ physical models.*

As advised by the technical team at Volvo Penta, the propeller was simulated using STAR-CCM+'s **Virtual Disc** model. This alters the flow around the hull to imitate what would have been if it was propelled by actual propellers. However, it does not simulate the suction of air towards the low pressure side of the propeller, and thus, it does not simulate the ventilation which causes a need for an AVP. This was not considered a problem as the main focus of the project was to optimize the hydrodynamic performance of the AVP, not its function. As such, all concepts were considered good enough from that point of view as long as the AVP width exceeded that of the propeller.

The computational domain was set up as a 3D-block with corners at coordinates $[-40.0, -20.0, -20.0]$ m and $[30.0, 20.0, 10.0]$ m, with the coordinate system origin at the transom of the 10 m (33 ft) generic hull provided by Volvo Penta. Mesh refinements were created at the free surface, around the stern drive, around the virtual disc, and at the hull transom. For resulting cell counts see Appendix C.

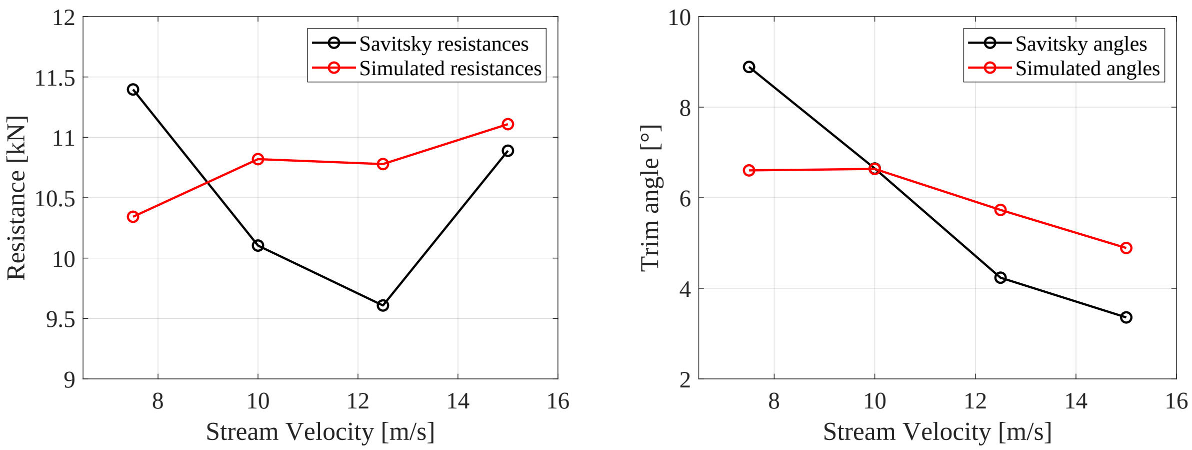
To reduce the required size of the free surface refinement, the vessel was set to an initial trim angle close to the expected equilibrium trim angle. As found reasonable from individual research, sterndrives were "mounted" in order to allow the AVP to be positioned about 15 mm above the hull's bottom.

5.1.2 Preliminary Concept Simulations

The initial set of simulations was run at a stream velocity of 10 m/s, with the initial trim angle set to 3°. This resulted in: **a)** trim angles at around 7° and **b)** some simulations crashing as the free surface moved out of the water level mesh refinements. This indicated that at 10 m/s, the hull had not reached full planing mode. To resolve this problem, the team decided to run a set of simulations on the hull in question to find where it reaches full planing mode.

5.1.2.1 Optimum Velocity and Trim Angle

The simulations were run at 7.5, 10, 12.5 and 15 m/s. As the Savitsky method described in section 2.2, theoretical results gave similar empirical trim angles at 10 m/s; whereas it was used to set the initial trim angles for the first set of simulations. The results in comparison with the predictions can be seen in figure 5.2.



(a) *Resistance* (b) *Trim angle*

Figure 5.2: *Simulation results.*

From the results, it was concluded that the best stream velocity to run simulations at was 12.5 m/s rather than the 10 m/s used previously. This decision came from a combination of both, the simulated trim angle and simulated resistance. At this speed, the team began closing in on a trustworthy trim angle value, all while the total resistance had yet to begin increasing notably due to high velocities.

Another set of simulations were carried out to find the optimum trim angle for the provided hull at the determined velocity. The angles initially tested were [1, 2, 3, 4, 5, 6, 7]°. As all the trim angles from the concept simulations were between 5° and 6° (see table 5.1), three points in that range ([5.25, 5.5, 5.75]°) were added later on. The results, presented in figure 5.3, show that the optimum angle is around 5.75°.

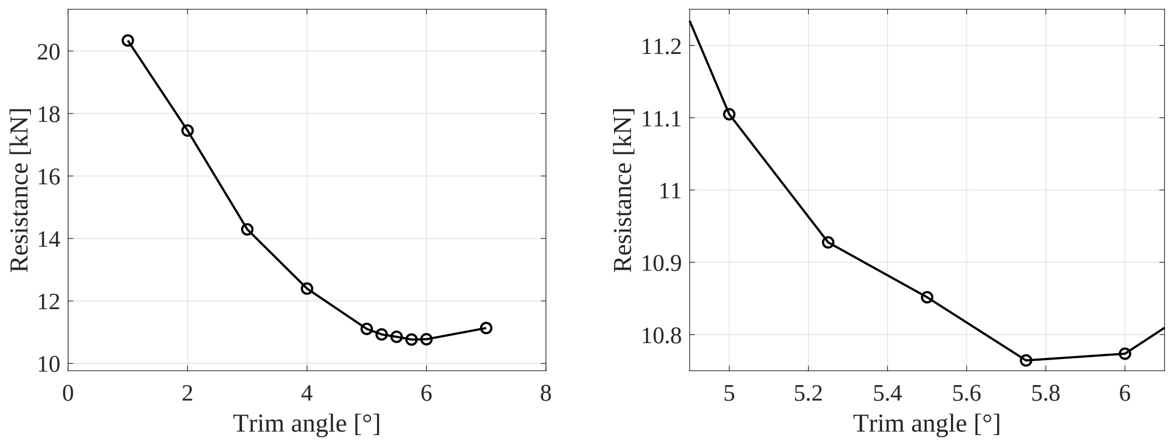


Figure 5.3: *Optimum trim angle.*

5.1.3 Concept Simulations

After optimum velocity and trim had been determined, there was sufficient data to set up the concept simulations in an efficient manner. The simulations were set up to run at a stream velocity of 12.5 m/s, and based off the results presented in figure 5.2b, the initial trim angle was set to 5.5°.

Simulations were carried out on concepts A, B, C, F, H, K, and L. For concept H, the variable sweep system, there was one simulation for maximum area and one for minimum area. This was done to simulate the "activated" and "deactivated" dynamic plate. Unfortunately, the simulation for concept B crashed, most likely due to that particular concept being a lot thinner than the rest. The mesh refinements needed to solve the problem resulted in an amount of elements that would have required too many CPU hours. Therefore, no simulations were completed for concept B. For the rest of the concepts, simulation data can be found in table 5.1.

Table 5.1: *Simulation data at 12.5 m/s.*

Concept	**Total resistance [kN]**	**Trim angle [°]**	**Stern drive resistance [N]**	**Stern drive lift force [N]**
Concept A	11.330	5.959	436.072	-2073.862
Concept C	10.959	5.848	319.725	-1484.914
Concept F	10.987	5.812	372.678	-864.033
Concept H_{in}	10.596	5.553	299.741	-260.748
Concept H_{out}	10.625	5.607	268.983	-139.068
Concept K	11.202	5.955	386.090	-1008.898
Concept L	11.477	5.084	1327.347	3436.201
Reference	10.829	5.626	490.478	-294.726

The main things to take away from this simulation data are:

- The only concept that outperforms the current Volvo Penta reference AVP in the most important metric, *total resistance*, is concept H. Note that this holds true for both cases of the concept's simulations.
- For hydrofoil shape of concepts A and F, the stern drive resistance was lower compared to the reference while the total resistance was higher. This seems to be due to the increased negative lift force, moving the trim angle away from optimum.
- It can also be seen that concept L successfully altered the trim angle, which increased the resistance at the prescribed velocity, but might decrease it at other velocities or if it is oriented at a different angle of attack compared to the drive.

To further examine whether or not it could actually be useful to alter the trim angle using the AVP, another set of simulations was carried out. This time the velocity was set to 10 m/s and simulations were only run on the reference AVP and Concept L. These simulations resulted in the data presented in table 5.2.

Table 5.2: *Simulation data at 10 m/s.*

Concept	**Total resistance [kN]**	**Trim angle [°]**	**Stern drive resistance [N]**	**Stern drive lift force [N]**
Concept L	11.192	6.046	1123.184	2893.992
Reference	10.895	6.824	228.698	-205.350

Once again, the reference AVP performs better in terms of *total resistance*. Moreover, while the *stern drive resistance* had increased by about 900 N when changing from the reference AVP to concept L, the total resistance had only increased by about 300 N. This indicates that the decrease in trim angle did reduce the hull resistance, just not enough to make up for the increase in sterndrive resistance. The increase in sterndrive resistance could also be due to the AVP obstructing the propeller jet stream, see figure 5.4. If this is the case, the angle of the AVP fin could be decreased slightly, despite that potentially decreasing the trim angle as well.

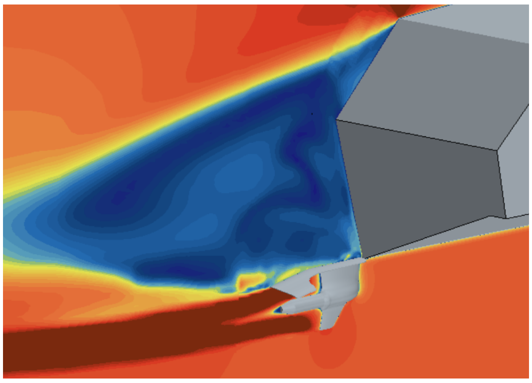
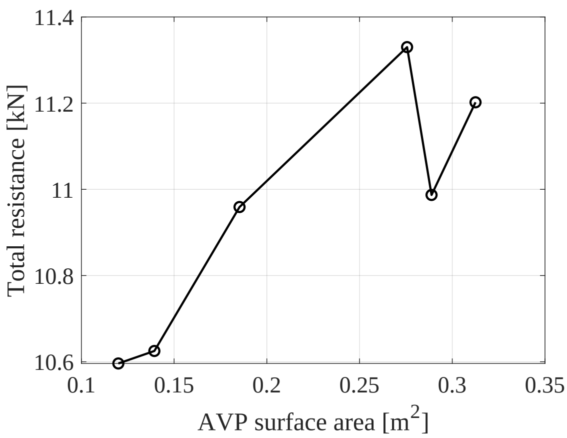


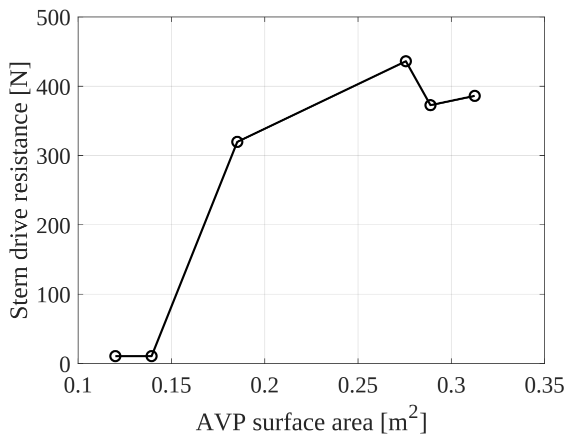
Figure 5.4: *Possible obstruction of the propeller jet stream by the fin of concept L.*

5.1.3.1 Significance of Surface Area

Throughout the project, AVP surface area had been considered an important parameter. In figures 5.5a and 5.5b one can see the relation between the resistances in table 5.1 and *SolidWorks* estimations of concept surface areas.



(a) *Total resistance in relation to AVP surface area*



(b) *Sterndrive resistance in relation to AVP surface area*

Figure 5.5: *Results in relation to surface area.*

As apparent in 5.5, there is no correlation between the size of the planform area and the resistance. There is a difference that can be seen, but the results indicate that there are more factors that impact the overall resistance of the boat and the sterndrive. Due to the fact that the concepts are different with regards to surface area, shape, and angle; the team could not determine a result that would lead to supported theory other than that there are different factors that contribute to the affect of total resistance.

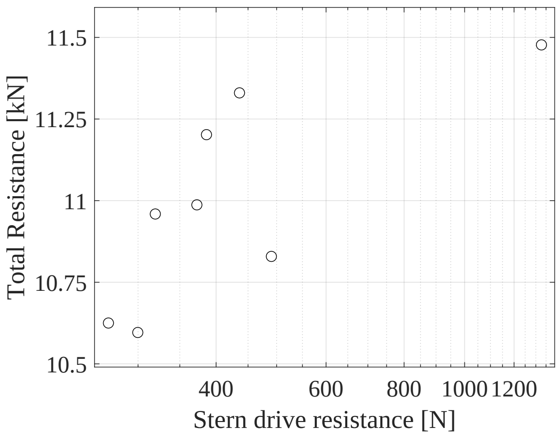


Figure 5.6: *Total resistance in relation to stern drive resistance.*

This can also be seen in figure 5.6, were the results show the relation between the resistance of the stern drive and the total resistance of the hull's system. Here, the results show that the sterndrive's resistance doesn't necessarily correlate with the total resistance.

5.2 Summary of Analyses

With these analyses carried out, a good foundation was laid for future development. Data that aids in the understanding of what is good and what is not was gathered from the simulations for optimum velocity and trim. For the individual concepts, enough data was gathered to get an idea of the benefits and consequences of different AVP features; where concept H stood out as the most efficient. The main problem remaining is that the amount of data gathered is too small to draw definitive conclusions and that it only covers one specific case.

6 Discussion

This chapter will discusses the approach and the results of the project regarding the objectives that were presented earlier in the report, as well as the ethical aspects.

6.1 Discussion of the Approach

One weakness in the results acquired through this project is that only the exact configurations that were imagined when the respective concepts were modeled, have been evaluated. This means that it cannot be known if a concept would have delivered much better results if a small parameter had been changed slightly. It also makes some concepts somewhat sensitive to the skill and effort put in by the person making the model.

A more scientific approach would have been to evaluate how each different parameter affects the result and thus, optimise these results. On the other hand, this would have severely compromised the diversity of the concepts, as the number of simulations grows exponentially with the number of parameters to evaluate, and each simulation takes more than 300 core-hours and an abundance of manual work. Since an important scope for the project was to come up with creative ideas, this approach would not have been optimal on its own. Moreover, it does not generate concepts outside the narrow limits reacting on each parameter, and hardly compares the initial parameters that differ in any other way than the initial measurements. However, it would likely make an excellent foundation to build on with the approach that was used within this project. Unfortunately, the combination of these two approaches did not fit within the time frame, as a lot of time was invested in learning how to perform these simulations. Nonetheless, it was a great learning experience and allowed the students involved to work within an inter-disciplinary engineering environment that allowed them to grow as a team, and as individuals.

6.2 Discussion of the Results

From the research conducted at the start of the project, it became obvious that two of the leading parameters that effect a boats efficiency are the closely connected trim angle and hull resistance. Focus then mainly involved finding ways to affect these parameters. The question is how effective different approaches were, and if they are worth further investigation.

6.2.1 Importance of Surface Area

During this project, the team analyzed several concepts with varying features. This typically resulted in an increased planform area due to including fins and curved models, which in turn, could be an underlying reason to why most concepts performed poorly compared to Volvo's reference. As seen in figure 5.5, there is certainly merit to trying to keep the AVP surface area as small as possible. However, as pointed out by the outlier in in the aforementioned figure, there is no definite correlation between AVP surface area and total resistance. A larger AVP could possibly result in lower energy consumption provided that other parameters and features are altered or optimised.

6.2.2 The Potential Value of Generating Lift Force

In the simulations carried out, there was no success in reducing total resistance by significantly altering trim angle; either because the induced AVP resistance was too large to be made up for by reduction in total resistance (concept L), or because the trim angle was altered in the wrong direction (concepts A and F). An interesting idea for further development of the concepts would be to then redesign the airfoil concepts, where significant down force was generated while actually reducing drag force compared to the reference. If it would be possible to keep the induced drag forces low, while generating lift force rather than down force, one might be able to positively alter the trim angle to reduce total resistance without increasing sterndrive resistance. The position of the AVP, further behind the point around which the hull rotates than any other part of the boat, makes it a prime candidate for generating this lift force. The distance makes it possible to create a larger bow-down moment than at other places without necessarily creating a larger resistance.

6.2.3 Leading Concept

In this project with the available time, concept H was found to be the leading concept. This is the AVP with an airfoil cross-sectional shape and a planform shape that can be varied between triangular design and that similar to Volvo's current AVP – attributed from a variable sweep aircraft. The only discontinuity was where the wings enter the main body, and the shell of the main body requires a thickness. There is one slightly unexpected phenomenon in the results though. The resistance and lift of the drive are lower when the wings are out and not the other way around. This is likely due to the difference in hull trim angle.

The possibility of limiting the surface area could be very beneficial. In some conditions, as mentioned in section 6.2.1, it could be valuable just for the sake of minimizing AVP wetted surface area. In other conditions, the airfoil section and the possibility to increase the width could be good traits for generating the necessary force to control the hull trim angle and, thereby, reduce total resistance.

There are so many variables that differ between each concept that it is too difficult to draw definite conclusions. This requires an abundance of simulations that would take thousands of core-hours, which is beyond the scope of this project due to time constraints. Because of this, the results presented are not adequate to make any final design decisions, but they might provide direction for future designs.

6.3 Ethical Aspects

This projects aim is to increase milage while reducing battery life on a boat with an electric powered sterndrive with a focus on the AVP. The option to change to an engine that performs better with an electrical powered one instead of one that runs on gasoline will benefit the environment. While this can also lead to some air pollutants in the world if the source of electric contributes to the environmental toxins, it can also be beneficial to have a electric powered engines with a clean power source that is better for the environment while also having a lower power consumption. The reduced power consumption is somewhat balanced though, by some 3000 core hours of simulations on the HPC computers and well over 100 hours of video conferencing on zoom and other computer or internet use during this project. This contributes to a lot of power consumption in servers around the world and subsequently, an environmental footprint [15].

In this project, the team was also aware of the aspect of safety. Though the material of the plate is a metal because it benefits the durability of the plate, it also led to a design specification. In the design, the plate was controlled to not have any sharp corners to make it safer for consumers, bystanders, and marine life.

7 Conclusion

With this project, the team had successfully gathered data on the hydrodynamic performance of a multitude of AVP features and concepts. It was found that at the very specific conditions simulated, concept H was the one for which the system as a whole consumes the least amount of energy. However, the fact that the concepts were only compared at one certain speed with the boat moving linearly means that further analyses would have to be carried out in order to definitively decide on a concept. Within that process, it would be a good idea to also combine the current concepts to ensure that valuable features that were not part of concept H would not be lost.

In section 1.2, a number of objectives that should be fulfilled over the course of the project were listed:

- **Develop an anti-ventilation plate that prevents air from reaching the propellers:**

  Because of STAR-CCM's Virtual Disc model was being used and the main project focus was to limit energy consumption; whether or not this was achieved is unclear. All designs were given dimensions that should be large enough to prevent ventilation based on knowledge about what has worked previously. To make sure that ventilation is prevented, this would have to be simulated and tested for the chosen concept.

- **Develop an anti-ventilation plate which induces low resistance to decrease the power consumption of the system:**

  As previously mentioned, at the conditions simulated, concept H managed to reduce the energy consumption compared to that of Volvo Penta's reference.

- **Look for anti-ventilation plate designs that generates forces that will positively impact the hull trim angle:**

  There were several concepts that successfully altered the trim angle of the hull, sometimes positively and sometimes negatively. The question that arose was whether or not it was possible to control when the angle was altered and if it could be done without inducing too much resistance on the AVP. For future development, the concepts from this project would have to be combined and/or refined in order to achieve a reduction in hull resistance that compensates for the increase in AVP resistance.

- **Consider both static and dynamic anti-ventilation plate designs:**

  Throughout the project, both static and dynamic designs were considered. There were, however, no investigations on what technical solutions to use to actually operate any of the dynamic designs. As pointed out above, it could be crucial to find a way to make this work in order to control when and how much the trim angle would be adjusted under various conditions.

References

[1] Volvo Penta. *VOLVO PENTA UNVEILS AN UPGRADED INBOARD PERFORMANCE SYSTEM (IPS) AND A BRAND NEW AQUAMATIC STERNDRIVE (DPI)*. URL: https://www.volvopenta.com/about-us/news-media/press-releases/2019/jun/volvo-penta-unveils-an-upgraded-inboard-performance-system-ips-/ (visited on 05/13/2021).

[2] Hank Johnston. *Is it cavitation or ventilation?* URL: https://www.louisianasportsman.com/fishing/is-it-cavitation-or-ventilation/ (visited on 05/13/2021).

[3] *Vera*. URL: https://www.c3se.chalmers.se/about/Vera/ (visited on 05/13/2021).

[4] *Simcenter STARCCM+*. URL: https://www.plm.automation.siemens.com/global/en/products/simcenter/STAR-CCM.html (visited on 05/13/2021).

[5] John J. Litjens et al. *U.S. Patent 4781632A. Anti-ventilation plate*. URL: https://patents.google.com/patent/US4781632A/en (visited on 05/13/2021).

[6] Killcare Marina. *Boating Performance*. URL: http://www.killcaremarina.com.au/commonly-asked/60-boating-performance (visited on 05/13/2021).

[7] Rolf Eliasson, Lars Larsson, and Michal Orych. *Principles of Yacht Design*. 2014. URL: https://ebookcentral.proquest.com/lib/chalmers/detail.action?docID=1569357 (visited on 05/13/2021).

[8] John O. Scherer and S.K.R. Patil. *Hydrodynamics of Surface-Piercing Outboard and Sterndrive Propulsion Systems*. 2011. URL: https://repository.tudelft.nl/islandora/object/uuid%5C%3A140deff0-139f-4298-85e8-1280766255b1 (visited on 05/13/2021).

[9] Elin Lindbergh and Felicia Ahlstrand. *Methods to Predict Hull Resistance in the Process of Designing Electric Boats*. 2020. URL: https://www.diva-portal.org/smash/get/diva2:1465549/FULLTEXT01.pdf (visited on 05/13/2021).

[10] Daniel Savitsky. *Hydrodynamic Design of Planing Hulls*. 1964. URL: https://onepetro.org/MTSN/article/1/04/71/172383/Hydrodynamic-Design-of-Planing-Hulls.

[11] *MATLAB*. URL: https://se.mathworks.com/products/matlab.html (visited on 05/13/2021).

[12] radii. *How to Brainstorm Effectively: Try Brainwarming*. URL: https://goradii.com/blog/how-to-brainstorm-effectively-try-brainswarming/#:~:text=Brainswarming%20is%20based%20on%20the,to%20create%20the%20brainswarming%20technique. (visited on 05/13/2021).

[13] Annie Sneed. *Brainstorming is Dumb*. URL: https://www.fastcompany.com/3062292/brainstorming-is-dumb (visited on 05/13/2021).

[14] *Solidworks*. URL: https://www.solidworks.com/ (visited on 05/13/2021).

[15] Renee Obringer et al. “The overlooked environmental footprint of increasing Internet use”. In: *Resources, Conservation and Recycling* 167 (2021), p. 105389. ISSN: 0921-3449. DOI: https://doi.org/10.1016/j.resconrec.2020.105389. URL: https://www.sciencedirect.com/science/article/pii/S0921344920307072 (visited on 05/13/2021).

Appendices

Appendix A MATLAB Script for *Savitsky Method* using Mercury Marine paper for appendage resistances.

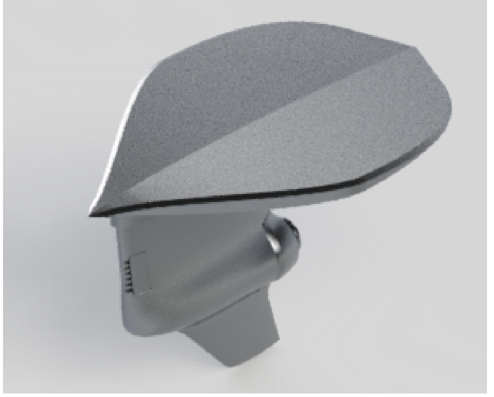
```
function [tau_0, R_tot, C_v] = SavitskyXMercury(V, epsilon, m, D_prop, t_strut, c_strut, A_strut, A_skeg, A_AVP)
    %% Input
    tau_all = [1 1.5 2 2.5 3 3.5 4 5 6 7 8 9 10];
    beta = 20; %deadrise angle of generic hull, degrees
    d_lambda_all = [1.5 1.05 0.77 0.62 0.52 0.43 0.38 0.29 0.22 0.18 0.12 0.10 0.08];
    %% Data
    % Hull measurements, generic hull
    VCG = 1.2;
    LCG = 3.3;
    b = 3.4;

    f_a = VCG;
    f = VCG+0.3;

    g = 9.82;
    rho = 1000;


    %% Drive related calculations [paper 852]
    % C_strut = 0.011;
    % C_skeg = C_strut;
    % C_D0torp = 0.2;
    % C_AVP = 0.003;
    % R_strut = 0.5*rho*V^2*C_strut*A_strut;
    % R_skeg = 0.5*rho*V^2*C_skeg*A_skeg;
    % R_AVP = 0.5*rho*V^2*C_AVP*A_AVP;
    % R_spray = 0.5*rho*V^2*(0.011*t_strut*c_strut+0.08*t_strut^2);
    % R_torp = 0.5*rho*V^2*C_D0torp*((pi*D_prop^2)/4);
    % D_a = R_strut + R_skeg + R_AVP + R_spray + R_torp;
    D_a = 0;

    %% Trim equilibrium
    % Step 2, 3
    C_v = V/sqrt(g*b);
    C_Lbeta = (m*g)/(0.5*rho*V^2*b^2);

    M = -1;
    it = 0;
    while M < 0
        it = it+1;
        % Step 4, 5, 6
        C_L0 = 1;
        TOL = 1E-10;
        fu = C_L0 - 0.0065*beta*C_L0^0.6 - C_Lbeta;
        while abs(fu) > TOL
            df = 1 - 0.0039*beta*C_L0^(-0.4); % wolfram alpha
            C_L0 = C_L0 - fu/df;
            fu = C_L0 - 0.0065*beta*C_L0^0.6 - C_Lbeta;
        end

```

```
        tau = tau_all(it);
        lambda = 1;
        fu = tau^1.1*(0.012*lambda^0.5 + 0.0055*(lambda^2.5/C_v^2)) - C_L0;
        while abs(fu) > TOL
            df = tau^1.1*((0.01375*lambda^1.5)/(C_v^2) + 0.006/sqrt(lambda));
            lambda = lambda - fu/df;
            fu = tau^1.1*(0.012*lambda^0.5 + 0.0055*(lambda^2.5/C_v^2)) - C_L0;
        end

        % Step 7, 8
        L_m = lambda*b;
        nu = 1.307E-6; Re = (V*L_m)/nu; %????
        C_F = 0.075/((log10(Re)-2)^2);

        % Step 9, 10
        d_lambda = d_lambda_all(it);
        R_f(it) = C_F*0.5*rho*V^2*(lambda+d_lambda)*(b^2)/(cosd(beta));
        f_f = VCG-(b/4)*tand(beta);

        % Step 11
        R_a = D_a;
        % Step 13, 14
        denom = (5.21*C_v^2)/lambda^2 + 2.39;
        L_cp = L_m*(0.75 - 1/denom);
        e = LCG - L_cp; % does not turn out as expected???

        %% Step 15
        M_h = g*m*((e*cosd(tau+epsilon))/(cosd(epsilon)) - f*((sind(tau)/(cosd(epsilon)))));
        M_f = R_f(it)*(f_f - e*tand(epsilon) - (f)/(cosd(epsilon)));%f??
        M_a = R_a*(f_a - e*tand(epsilon) - (f)/(cosd(epsilon)));%f?
        M(it) = M_h + M_f + M_a;
    end
    i = length(M);
    tau_0 = tau_all(i-1) + (M(i-1)*(tau_all(i)-tau_all(i-1))/(M(i)-M(i-1)));
    R_f_0 = R_f(i-1) + (R_f(i) - R_f(i-1))/(tau_all(i)-tau_all(i-1))*(tau_0-tau_all(i-1));
    R_tot = (g*m*sind(tau_0)+R_f_0)*((cosd(tau_0+epsilon))/cosd(epsilon));
end
```

Appendix B Rendered CAD Models of Assembled Concepts.

Concept A:

This concept depicts concept 1 from the combination table. It is an assembled version of the anti-ventilation plate mounted onto Volvo's sterndrive. It has an airfoil cross-section with a teardrop planform area. Concept 13, a dynamic concept, mimics concepts A which is why no simulations were ran on it.

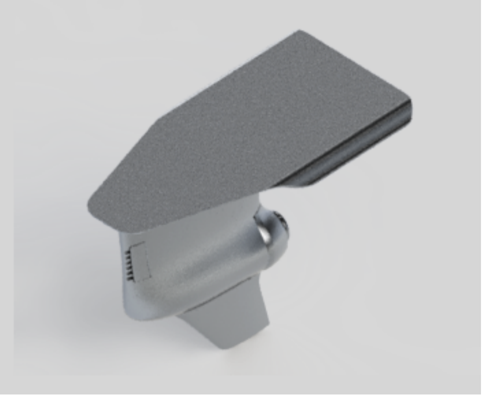


Concept B:

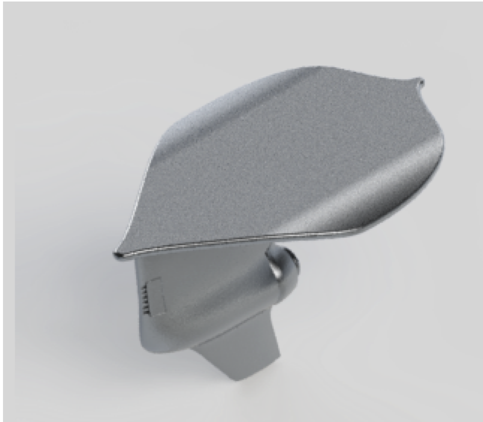
This concept depicts concepts 2 from the combination table, but doesn't mimic any other concepts as it is unique and requires its own simulation. The plate is triangular shaped and has fins mounted on the lower side of the anti-ventilation plate. These have the purpose of preventing sidewards flow under the plate which is hoped to prevent ventilation, though no simulations have been performed on that matter.

Concept C:

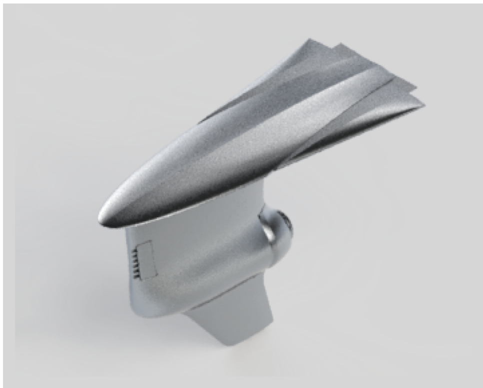
This concept depicts concept 3 from the combination table. It is of a typical rectangular plate but had the addition of winglets. Upon assembly, it should be angled downward in order to aid in trimming of the hull as. Concept 7, a dynamic concept, mimics concepts C which is why no simulations were ran on it.



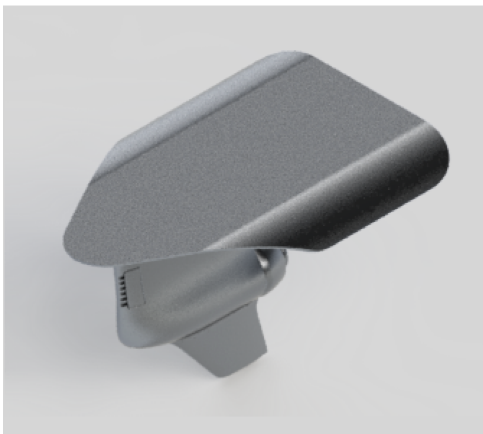
Concept F:
This concept depicts concept 9 from the combination table, but doesn't mimic any other concepts as it is unique and requires its own simulation. It has a slight curvature around the propeller with a teardrop shaped planform area. It is also able to pivot vertically, where within simulations the angle is altered slightly for multiple analyses.



Concept H:
This concept depicts concepts 11 from the combination table, and doesn't mimic any other concepts as it is unique and requires its own simulation. The plate can change shape between triangular and similar to Volvo Pentas current AVP, and has an airfoil section shape. Concept I, a similar concept but flat instead of an airfoil cross-section, mimics concept H which is why no simulations were ran on it.



Concept K:
This concept depicts concept 14 from the combination table, but doesn't mimic any other concepts as it is unique and requires its own simulation. It has an nonagressive curvature around the propeller with a triangular planform area. Although hard to simulate, it is able to pivot horizontally, either on a spring or actuator, due to side forces acting on it.



Concept L:
This concept depicts a concept that was later added after them team recieved a suggestion from their CFD Advisor, Arash. concept 14 from the combination table, but doesn't mimic any other concepts as it is unique and requires its own simulation. It has a slight curvature around the propeller with a triangular planform area. Although hard to simulate, it is able to pivot horizontally, either on a spring or actuator, due to side forces acting on it.

Appendix C Simulation Cell Counts

(a) *Cell counts for the main set of concept simulations at* 12.5 $^{m}/_{s}$

Simulation	Cell count
Concept A	4 016 155
Concept B	4 230 551
Concept C	4 122 360
Concept F	4 500 658
Concept H_{in}	4 523 581
Concept H_{out}	4 479 132
Concept K	4 061 804
Concept L	4 050 419
Reference	4 576 361

(b) *Cell counts for concept simulations at* 10 $^{m}/_{s}$

Simulation	Cell count
Concept L	4 020 527
Reference	4 568 186

(c) *Cell counts for optimum velocity simulations*

Simulation	Cell count
7.5 $^{m}/_{s}$	2 617 984
10 $^{m}/_{s}$	2 669 457
12.5 $^{m}/_{s}$	2 971 775
15 $^{m}/_{s}$	2 786 515

(d) *Cell counts for optimum trim angle simulations*

Simulation	Cell count
1°	2 861 161
2°	2 819 469
3°	2 786 533
4°	2 753 509
5°	2 720 478
5.25°	2 710 354
5.5°	2 702 610
5.75°	2 695 029
6°	2 684 669
7°	2 651 771