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Design and system integration of a rim jet solution utilizing DFMA

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Abstract

Moving a new innovative idea from the drawing board to production is no easy feat. The Swedish sea rescue society (SSRS) has for the past years fostered a new design solution for their jet skis, a alternative water jet that removes the centre hub and utilises rim drive technology. The "Rim Jet" would help solve problems during rescue operations while at the same time be a starting point for SSRS zero-emission vision. To make this idea reality a first prototype is necessary for a proof of concept. Previous work on this project, conducted by three master students, resulted in a design that lacked feasibility. Through the implementation of Design for manufacture and Assembly (DFMA) on the rim jet a new iteration of the design is proposed. A practical and case based analysis of the DFMA method on a novel, non mass produced prototype was preformed discussing its advantages and disadvantages to generate a feasible, lighter, simpler and more cost efficient design. Complementing the redesign of the rim jet is a complete systems analysis of the jet ski including battery evaluation, systems integration and initial testing procedures. The final rim jet design illustrates the benefits of utilising DFMA within small, single product, projects. Implementing core elements of DFMA has proven to generate similar positive effects as intended for serial mass produced products normally associated with method.

KTH Industriell teknik
och management

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Design och systemintegrering av en rim jet-lösning med hjälp av DFMA

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Sammanfattning

Att föra en ny innovativ idé från ritbordet till produktion är ingen arbiträr process. Det Svenska Sjöräddningssamhället (SSRS) har under de senaste åren fostrat en ny designlösning till sina vattenskoter, en alternativ vattenjet som eliminerar centrumnavet och använder rim-drive teknologi. Rim Jetenskulle hjälpa till att lösa problem under räddningsoperationer samtidigt som den kan agera som utgångspunkt för SSRS-nollutsläppsvission. För att förverkliga denna idé är en första prototyp nödvändig för att bevisa om konceptet kan fungera. Tidigare arbete med detta projekt, genomfört av tre masterstudenter, resulterade i en design som ej gick att tillverka. Genom implementeringen av Design for manufacture and Assembly (DFMA) på rimjeten kan en ny designiteration läggas fram. En praktisk och fallbaserad analys av DFMA-metoden på en ny, icke massproducerad, prototyp genomfördes och dess fördelar och nackdelar diskuteras för att skapa en genomförbar, lättare, enklare och mer kostnadseffektiv design. Som komplement till den nya designen kompletteras även arbetet med en en fullständig systemanalys av vettenskootern relaterat till betterilösning, systemintegration och initiala testutföranden. Den slutliga rim jet designen illustrerar fördelarna med att använda DFMA inom små, enskilda produktprojekt. Implementeringen av kärnelement från DFMA har påvisat liknande positiva effekter som avsedda för serieproducerade produkter som normalt är associerade med metoden.

Nomenclature

F	Force $[N]$
H	Headrise $[m]$
N	Newton
P	Power $[W]$
Q	Volume flow $[m^3/s]$
rpm	Rotations per minute
T	Torque $[Nm]$
V	Volt
v	Velocity $[m/s]$
W	Watt
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
CNC	Computer Numerical Control
DFA	Design for Assembly
DFM	Design for Manufacture
DFMA	Design for Manufacture and Assembly
ITTC	International Towing Tank Conference
KTH	Royal Institute of Technology
PMI	Product Manufacturing Information

RDP	Rim Driven Propulsion
RDT	Rim Driven Thruster
RS	Rotor Side
SKF	Svenska Kullager Fabriken
SS	Stator Side
SSRS	Svenska Sällskapet för Räddning af Skeppsbrutne

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Chapter 1

Introduction

Swedish Sea Rescue Society, or SSRS, is a nonprofit organisation that conducts maritime search and rescue operations on Swedish lakes and at sea. They operate both individually and together with the Swedish coastguard. Their work is diverse and often demanding. It is therefore of importance that they have the right equipment for the task at hand and that said equipment does not break during operations.As of now the SSRS disposes of a wide array of sea vessels one type of which is their Rescuerunner (Swedish Sea Rescue Society, 2020). This craft is designed as a more stable and competent water scooter in sea rescue operations. It was designed and developed by Fredrik Falkman at SSRS and later bought by Safe at Sea in 2006 (Safe at Sea, 2020). The Rescuerunner has been in regular use by SSRS ever since its conception but issues with the current solution has arisen. One of the major problems that were discovered by Falkman early after implementation was issues with engine failure due to entanglement from ropes and other debris in the water from ship wreckages. The motor blades rotate at such a speed that, when entangled, the plastic ropes melt and hardens around the motor which require expensive and time consuming repairs. A new type of engine was needed, Falkman started to foster plans for one that removes the centre hub which potentially could reduce the risk of entanglement. The solution should be electric, both from a sustainable point of view as well as a functional. For most commercial mid and large size crafts the more common screw propeller is a cheaper and simpler choice. But with the emerging trend of electrical transportation, especially within the vehicle market, there is a possibility that this will be the future for maritime transportation as well.

The first step made toward this new solution was done by Thor Andersen who wrote his master thesis "Design of Rim Driven Waterjet Pump for

Small Rescue Vessel" in 2014 (Andersen, 2014). Since then, three master students have worked on the project with the aim to generate a functioning solution. Despite their efforts, the Rim jet is still not feasible in its current state. With complicated, costly and impossible geometrical shapes as well as a convoluted assembly structure and high part count the design was not fit for manufacturing. To realise the rim jet a new method of deigning will have to be implemented to make the design feasible. This master thesis aims to further develop and advance the concept of the rim less water jet through the method of Design for Manufacture and Assembly (DFMA). DFMA is a combination of "Design for Manufacture" (DFM) and "Design for Assembly" (DFA). The method was developed by Geoffrey Boothryd in the beginning of the 1970s and was practically adopted within a wide array of corporations from the 1980s. DFMA is used as a driver for quality and cost improvements within product development. The method balances both the manufacturing aspect as well as the assembly aspect of developing new products with the purpose of optimising the final product as a complete system.(Boothroyd, 2002). Through adoption of DFMA to this thesis, evaluation of the principles will be conducted to investigate the pros and cons of DFMA on a singular product.

Chapter 2

Theory

2.1 Theory

Within the engineering community DFMA is often promoted as the optimal design method, even though no comparative studies have been performed. One example is the costly implementation of DFMA within product design software, utilising virtual reality to provide engineers with instant feedback on their work as illustrated by A. Read et al., 2017,. (Read et al., 2017) Nevertheless, since the conception of DFMA, the potential and possible limitations of the method itself has been evaluated within scientific research. In a paper from 2011 . A. A. Sarmento et.al. preformed a successful case study on a Fuel Intake Cover to simplify the already relatively simple design(Sarmento et al., 2011). A second case study by N.M. Azir used DFMA and a sustainable design approach to evaluate and improve the design of a Cordless Drill(Azri et al., 2018). A third study by C.D Naiju et al. used DFMA when redesigning a shopping cart, with both reductions of the manufacturing and assembly costs as a result. (Naiju et al., 2017).

According to the examples presented above, when evaluated within itself, DFMA proves to be a successful method. The majority of case studies found within the subject are limited to small and relatively simple products. However, in 1998 E. H. Gerding et al. at the Boeing Company published an article on how to successfully implement DFMA to their already existing aircraft production, proving the method's validity within more complex projects. (Gerding et al., 1998). Gerding et al. point out that implementing DFMA on pre-existing products can prove more difficult than when generating new concepts. Boeing's article present many of the pitfalls that can occur during implementation, possible solutions, as well as tools and guidelines to improve the use of DFMA within an organisation.

DFMA is mostly regarded as a tool for improving product design related to series- and mass production(Matthews et al., 2018). The foundation for this viewpoint was laid by Boothroyd, but additionally he claimed that DFMA should be applicable to low volumes as well. He argues that the philosophy of "doing it right the first time" is of even greater importance when producing small quantities. However, the work presented by Boothroyd is primarily focused around mass production and improvements of already existing solutions, as exemplified by Boeing. When comparing the improved design to the previous an array of tests are conducted. Most frequently, designers opt to measure the assembly time and manufacturing cost of each individual part. This method of testing has proved to be an issue when assessing low quantities or a singular unit. Matthews et.al. investigates this problem using a case study involving a manufactured Paperboard Tray Press-forming prototype line. With DFMA they were able to improve the existing product resulting in less injuries when assembling the unit as well as avoiding unnecessary reassembly cycles of the design.

With the emergence of Rapid Prototyping within product development a new research area combining DFMA and Rapid Prototyping has been investigated. In the paper "New product development by DFMA and Rapid Prototyping" by W. N. Prakash et al. a case study was used to evaluate the combination of both disciplines. DFMA was used to re-design a flow control valve. Utilising the Rapid Prototyping, a proof of concept could immediately be tested. The outcome proved to be an optimal design with low costs, good quality and fast delivery to the customer(Prakash et al., 2014). Although the improved product presented by N. Prakash et al. is a prototype, it could be argued that it is still related to mass production in view of the fact that it is later on intended for large scale production.

Another aspect when discussing DFMA is its close but undefined connection to a platform- and modular design approach. F. J. Emmatty and S. P. Sarmah highlighted the many similarities between DFMA and platform-based design and questions why there has been no attempts to combine the two. Their work provides a case study implementing a modular approach through platform-based design with the principles provided in the DFMA method. Their end result proved to be an optimal product platform with reduced development time for product families(Emmatty and Sarmah, 2012).

In summary, DFMA is seen by the engineering community at large as the optimal design method, even though it is mostly evaluated within itself. When designing new or improving existing products, may it be an airplane or a simple toaster, there is a multitude of personnel and disciplines involved. Deciding the best way to manage these aspects of a design process is key to generating an optimal design solution. Following a common set of rules and principles can ease this interaction and improve over all work quality. DFMA has previously proven to benefit both small and large scale products. Nevertheless, when examining the current status of DFMA most implementations are, in some way or another, connected to mass production even when the concept of prototyping is discussed. Because of this, there is still a research gap when discussing DFMA and a modular approach on a singular product that might never be in mass- or even serial-production.

2.2 Method

Implementing principles and methods from the book Product Design for Manufacture and Assembly (Boothroyd, 2002), the use of DFMA was applied to the Rim Jet to investigate the possible benefits of the method on a singular unit and improve on the current design.

Given the work by Boothroyd, the key principles of DFMA related to this project is:

- Reduce the part count; A key factor for a more cost effective and simpler design is the reduction of parts within the product. Fusing together parts that do not have to move relative to one another, such as the rotor tube and Bearing Positioner SS (illustrated in subsubsection 5.3.1), reduces the part count as well as simplifies manufacturing and improves durability of the design.

- Use standardised parts and materials; To simplify assembly as well as reducing cost and finding replacement parts the use of standardised parts is essential. All bolts and screws for the rim jet are chosen with standardised M thread as well as generic lengths to minimise the variations of chosen sizes. Regarding materials for the rim jet, compromises were made on the exact type of material as it depends on what the manufacturer can offer. However, the selection between aluminium and stainless steel is of importance as their inherent proprieties and raw value will affect the final cost. As unprocessed material, stainless steel is usually cheaper then aluminium. However, the tooling cost for machining stainless steel is much higher then aluminium. For this project weight is also a big factor, reducing the total weight of the engine will result in a lighter total vessel and in turn a reducing in the battery needed as well as other positive property changes on the craft.

- Reducing and simplifying the number of manufacturing operations; As mentioned previously, tooling cost is a big factor when deciding on the right materials for a part. Another aspect when designing individual features is to understand the methods that will be used to create said feature. If a shape is to complicated or requires a special set of tools to accomplish it should be reevaluated and changed if possible to simplify manufacturing. One such obvious area is the notch on the rotor tube that currently requires two tubes to be welded together to accomplish.. This manufacturing method is both costly as it requires a multitude of processing steps as well as being unpredictable when regarding tolerances of the centricity of the tube.

- Simplifying the design for an easier assembly procedure; Both first assembly as well as later modifications would benefit from a design that optimises simplicity during assembly. Especially during the prototype phase of the design there might be a wide array of changes that will have to be made later to optimise the deign. Designing in a way that is simple to assemble and disassemble will reduce both manufacturing cost as well as future modification cost.

- Design modular assemblies; A modular approach ties together with the previous simplification of the design. Within this project one major area of modality is the blade construction and configuration. However, this blade design has yet to be tested in a real life scenario. It is therefore essential to design in a way that simplifies future changes made to improve the fluid properties of the blades. Therefore, a modular approach is implemented especially within that area to account for possible future changes.

Presented in Chapter 5 all individual parts within the rim jet are evaluated in regards to previously mentioned areas of DFMA. No aspect can be evaluated without regarding the others and a design decision should always be weighted against other aspects and most of the times compromises must be made to reach an optimal design.

With the use of CAD software, the previous design was improved through implementation of iterative DFMA. Using methods for rapid manufacturing and modular design provided in the book Collaborative Engineering (Kamrani and Nasr, 2008) in tandem with DFMA presented in the paper written by Prakash et al. (Prakash et al., 2014) both the Rim Jet as well as the Rescue Vessel was improved as a complete system.

Utilising this hands on case of a single unit rim jet, DFMA can be evaluated from a new perspective and providing insight to its pros and cons even for small quantities of produced units.

Finally, using recommendations provided by the International Towing Tank Conference, cost efficient and simple testing methods were derived.

2.3 Market Overview and Related Research on RDP

For the past few years new actors on the electrical maritime market have been emerging and the public interest in electrical transportation has never been higher. In Sweden there are two big actors, Candela (Candela, 2020) and XShore (XShore, 2020). Their products are both completely electric but attempts to solve the issues with electrical driven water crafts in different ways. Candela has chosen to implement foils in their design to overcome the drag from water on the hull, whilst XShore has chosen a bigger battery to counter the resistance from the water. Currently both of these companies use a regular propeller for propulsion, this is also the case for other companies on the market such as Strana (Starna, 2020) and HWILA25 (Hwila25, 2020).

Another type of water propulsion is the rim driven propeller, most commonly used on bigger container ships as prow and stern thrusters to move the ship sideways. One of the leading manufacturers for smaller water crafts are the German company Torque-Jet (Torque-Jet, 2020). They have adapted the regular bow thruster to be used as a propulsion motor by reshaping the blades and adapting other properties to be more effective in one rotational direction. Furthermore, a French company named FinX have developed a membrane motor that removes any rotating parts and instead uses a wave-like motion to move the water through the engine (FinX, 2020). The motor is said to be safer and more robust than conventional propellers. The current models are still in development but pre-orders can be made.

Research on the subject of rim driven propulsion as a valid substitute for propellers as propulsion is relatively scarse, although companies that are currently developing and manufacturing this type of machine most certainly have their own confidential research on the subject. There have been research done by the School of Marine Science and Technology in China where they, much like Andersen, compared hub-type and hub less rim driven thrusters to analyse efficiency and other aspects of the configuration(Song et al., 2015). Their research concluded that a hub-less design would be have an increased thrust, a higher torque and a smaller thrust ratio compared to using a hub in the middle of the rotor. The same finding was also concluded in the work by Lan et al. in their work "Study on Hydrodynamic Performance of Hubless Rim-Driven Propulsors with Variable Parameters"(Lan et al., 2017). However, both of the studies was preformed on a standard rim-driven thruster at relatively low rotational speeds (approximately 1000 rpm) and not with a jet-configuration. Another research project from University of Southampton investigated the rotor–stator interaction in rim driven thrusters to better understand the fluid dynamics related to this design solution (Dubas et al., 2015). Dubas et al. conclude that the methods used in the study lack in accuracy and that further studies on the subject should be conducted to better understand and predict the effects of rotor–stator interaction.

In 2017, engineers S. Fletcher and R. Hayes at Frazer-Nash Consultancy presented a pros and cons discussion on the future of electrical propulsion. They state that the shipping industry has seen a shift during the recent years in the use of technology and that integration of electrical propulsion is emerging (Fletcher and Hayes, 2017). They also discuss the potential of Rim-Driven Propulsors (RDP) and the benefits that this technology could have for the future of ship architecture. One key area Fletcher and Hayes present is the efficiency potential of a RDP. More specifically, the lack of a centre hub or shaft that would reduce the potential energy loss from turbulence, while at the same time increasing the control over rapid changes in the rotational speed. In a paper from The Hong Kong Polytechnic University Cheng et al. discuss zero emission electric vessel development. It is concluded that the emerging trend of electrical water vessels will result in the replacement of short range vessels within the next ten years (K.W.E. et al., 2015).

In a paper review written by Yan et al. from 2017 it is concluded that

> "Rim-driven thruster (RDT) propulsion device has several notable advantages compared to the traditional shafting propulsion plant

> and POD propulsion plant (e.g., better working principles, easier product maintenance, and occupying less engine room space), but also that high-power RDT propulsion devices are considerably more complex. High-power driven motors and high-load carrying, wear-resistant, water-lubricated bearings have yet to be fully developed." (Yan et al., 2017).

As stated above, rim driven propulsion has potential to be the future of water propulsion if the specified technical obstacles can be overcome. In their review, a number of cases are listed that research the use of rim driven, as well as shaft less rim driven thrusters. In their list, only the work done by Andersen investigates the use of rim thrusters in a water jet configuration.

2.4 Purpose

In a world where climate change is affecting everyone, new leaps for a more sustainable future is made every day. Electrical cars are now something most have grown accustom to, although this was not the case 10 years ago. As mentioned earlier, Cheng et. al predicts in their paper from 2015 that in ten years electric solutions will be replacing small short range vessels. Moreover, Dubas et al. concludes in their paper that further research in the area of rotor stator interaction regarding rim driven propulsion would be of considerable value to a number of applications (Dubas et al., 2015).

This project builds on previous work on the Rim Jet solution first started by Thor Andersen six years ago with the aim to theoretically validate if a Rim Jet solution for SSRS could be sufficient. Andersens thesis concluded that a Rim Jet design could work in practice with some minor efficiency set back because of the loss of a centre hub (Andersen, 2014). Following Andersen was Pablo Sánchez Santiago and most recently Magnus Munoz. Munoz suggested that future research should focus on a prototype validation and investigate the integration of the Rim Jet with the Rescue Boat.

Before production can begin the design of the Rim Jet must be finalised, assuring that all parts can be both manufactured individually and assembled as a unit. The production methods chosen must be reasonable in cost and accuracy as the budget for SSRS is limited. Moreover, the assembly and disassembly of the product must be valid and optimised for changes and future improvements. The method of DFMA is most commonly used for products in large quantities, however in this research core principles will be used to investigate and evaluate the potential of DFMA on a single prototype, in this case the Rim Jet with hopes that the philosophy of DFMA will improve the overall design.

Hence, the purpose of this project is to further develop and advance the concept of a rim less water jet using DFMA. Both for the potential use within SSRS as a tool for rescue operations, but also to further investigate rim driven propulsion regarding RDT as a valid option for smaller maritime vessels which operate at higher speed. Through adoption of DFMA to this case study, evaluation of the principles will be conducted to investigate the pros and cons of DFMA on singular product and fill the research gap within this area. The project will also include a proposal for system integration and preparations for upcoming testing, with the aim to provide recommendations for up coming work on the Rim Jet and Rescue Vessel project as a whole.

2.5 Limitations

The limitations for this thesis are:

- No major changes will be made to the current design. However, reducing and simplifying the current drawings for manufacturing will be done.
- The methods used for manufacturing are chosen in regards to their time efficiency and cost for one unit. It might therefore be important to change manufacturing methods for future products to reduce production costs.
- No Computational Fluid Dynamics (CFD) simulation will be made within this project as the time for this project is limited.
- The current engine provided by SSRS for the project has a smaller hub diameter than previous calculations done by students have accounted for. However, no changes to the engine can or will be made at this stage and the goal is therefore in this thesis to design a working prototype with the current engine.

Chapter 3

Frame of reference

3.1 Water Jet Propulsion

Water jet propulsion as a concept dates back to 1661, but it is only in later years that its potential use on larger water vessels have been considered Carlton (2012). A water jet utilises Newtons second law of motion “Every action has an equal and opposite reaction”. Water is drawn in from underneath the craft, into the pump house and then forced out through the exit nozzle. This flow of water generated by the rotor is what pushes the craft forward. See Figure 3.1

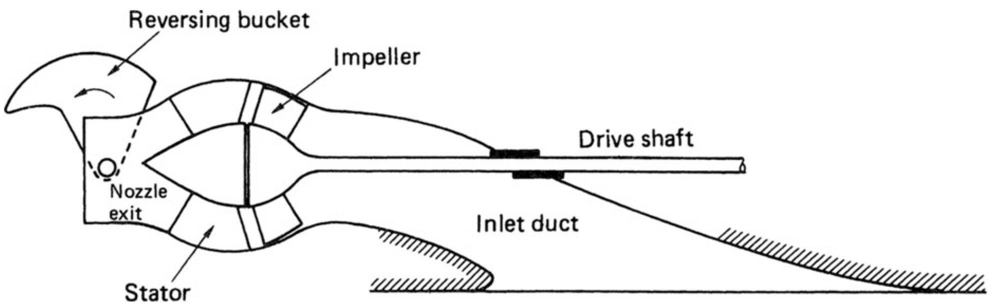

Figure 3.1: Principal drawing of a water jet Carlton (2012)

Water enters the inlet tube from underneath the craft, it is then lead into the rotor blades and accelerated towards the rear. The rotating impeller blades are formed like screws to transfer the energy from the engine to the water, whilst the stator blades have a more axial angle to straighten the flow of the water for higher efficiency. Water then exits the jet from the steering nozzle which usually is used to control the direction of water and hence steer the vessel. To reverse the flow on a water jet a reversing bucket is used. Through a mechanic or hydraulic actuator it is possible to go from full forward thrust to full reverse within seconds. For some designs of the reverse bucket, it is also possible to use the full capacity of the water jet when manoeuvring the craft by spilling some of the water backward and forward at the same time. This makes it possible to rotate the vessel without moving it backward or forward.

3.2 Rim Driven Propulsion

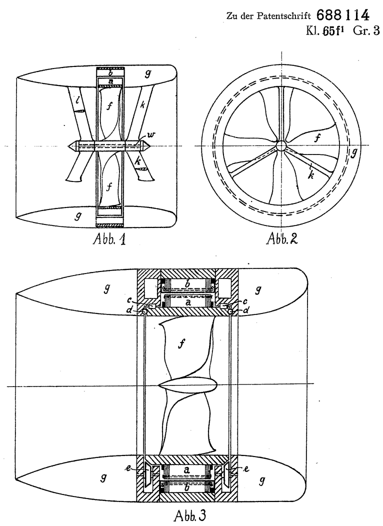

Figure 3.2: Drawing from the German patent f or a RDT (Kort, 1940)

Rim Driven Thruster (RDT) or Rim Driven Propulsion (RDP) is an alternative solution to the traditional shaft transmission solution. The rudimentary principal of a RDT is, compared to classical propulsion techniques, to move the origin of rotational force from a centre axle to the outer rim of the tube. This means a compleate removal of the drive shaft as depicted in Figure 3.1. RDP as a concept has been around since the early 20th century, with different design solutions and patents. Shown in Figure 3.2 is a German patent from 1940 that was meant to be powered by electricity. It should be noted that the design depicted still utilises a center hub for blade stabilisation in contrast to the rim jet design in this project. Other transmission solutions tried to utilise gearboxes to transfer the energy but proved to generate to much friction and energy losses. (Satterthwaite and Macy.Jr, 1970).

RDTs of today primarily use magnets to set the rotor in motion. The housing, illustrated as b) in Figure 3.2 drawing Abb.1 is static and mounted to the craft and consists of several electromagnets. The rotating ring a) has multiple small permanent magnets mounted around the blades on a tube. By altering the current through the electromagnets the rotor is set in motion, in the same was as any electrical motor.

3.3 The Rescue Vessel

Figure 3.3: The original Rescuerunner developed by Fredrik Falkman. Swedish sea rescue society (2020)

Currently in use by the SSRS is the Rescuerunner(SafeAtSea, 2020), a small water craft designed by Fredrik Falkman at SSRS for their operations. The boats hull is designed to be stable and durable in harsh sea while providing the driver with easy manoeuvrability and power. The Rescuerunner is built to access places larger crafts can not and the relatively small size also makes it easy for one person to operate.

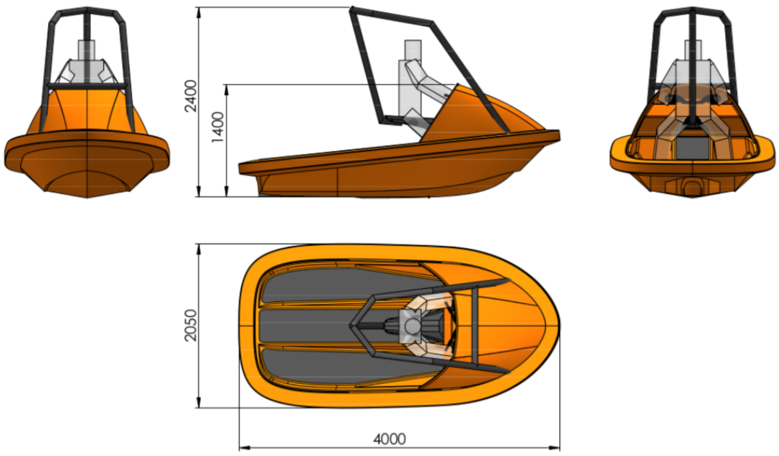

Figure 3.4: The new Rescue Vessel designed by Fredrik Falkman

Since then, the ownership and production of the Rescuerunner has been acquired by Safe At Sea, however Fredrik Falkman has been developing a new type of rescue craft. This water craft is slightly bigger than the original Rescuerunner but is still as reliable and durable as its predecessor. Currently there has only been one prototype produced with the intention to work as a testing unit for the potential Rim Jet.

3.3.1 Technical Requirements

In the beginning of this project in 2014 SSRS decided on a list of requirements that had to be met for them to determine if the final vessel would be of use to them. In Table 3.1 the requirements are listed.

Table 3.1: Requirements set by SSRS on the final vessel

SSRS Requirement	**Value**	**Unit**
Bollard pull (thrust)	4	kN
Engine maximum rotational speed	4000	rpm
Maximum torque	132	Nm
Delivered power at maximum rpm	55	kW
Vessel speed	20-25	knots
Displacement	800 (1250)	kg

Chapter 4

Previous Work

4.1 Thor Peter Andersen

Thor Peter Andersen, a master student at Chalmers University of Technology, laid the foundation of which all subsequent projects build on. In his paper "Design of Rim Driven Waterjet Pump for Small Rescue Vessel" Andersen simulated different design possibilities of the Rim Jet and aimed to verify if a hub-less Rim Jet is theoretically possible in regard to the requirements set by the SSRS. He concludes that the Rim Jet could be a feasible solution, but that efficiency and bollard pull (thrust at zero knots) will be an issue due to the size of the rotor diameter. Andersen proposed future work to improve on the cavitation properties of the system and that, if possible, the best improvement to the design would be to increase the diameter of the rotor as well as the outlet. In addition he also pointed out that the lack of accuracy and exact data on the duct losses could potentially mean that a real prototype of the Rim Jet could have a higher bollard pull if duct losses are lower than his simulations concluded and that future research would benefit from further investigations within this area.

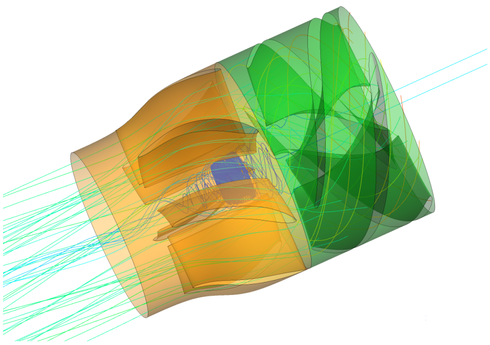

Figure 4.1: Blade design by Thor Peter Andersen

4.2 Kiran Ashok Naganalli

Shortly after the work by Andersen was published a student from KTH begun working on a first design for the Rim Jet. However, this work was never finished as the student left Sweden without notice and was never heard from again. What was estimated to be almost half of a finished report was received by SSRS but little have been used from said work.

4.3 Pablo Sánchez Santiago

Taking over after Andersen was Pablo Sánchez Santiago who made the first technical concept of the Rim Jet. He used bearings from SKF and seals from Trelleborg Sealing Solutions together with custom designed parts that had to be made separately. The work was primarily focused on determining the most fitting bearings and seals that would withstand the forces and rotational speed of the engine, whilst taking into account the importance of minimising the number of systems, optimising performance and making the end product as compact as possible.

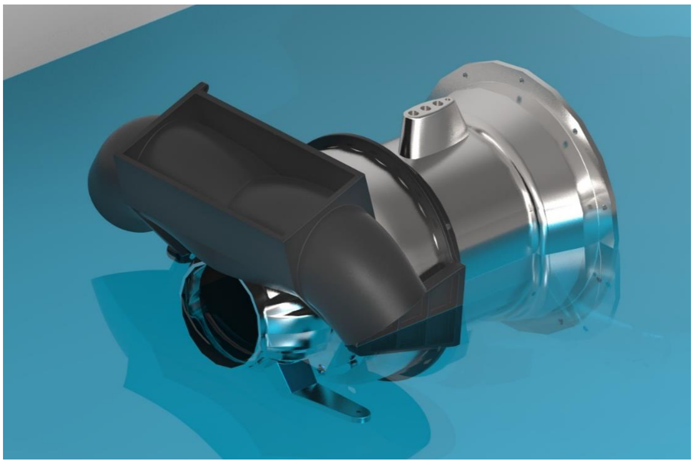

Figure 4.2: Rim Jet design by Pablo Sánchez Santiago

4.4 Magnus Munoz

The work done by Sánchez Santiago was then handed over to Magnus Munoz for further development. In his thesis "Mechanical design and manufacturing evaluation of a shaftless waterjet propulsor" the primary objective was to evaluate and finish the current design proposed by by Sánchez Santiago and investigate different manufacturing techniques that could be used to produce the first prototype. Focus was directed toward reviewing and editing the previous design and using Finite Element Method (FEM) to evaluate the concept. In addition, Mũnoz initiated a collaboration with SKF, a partnership that has continued throughout this project. SKF is intending to manufacture the first prototype of the Rim Jet.

Figure 4.3: Rim Jet design by Magnus Munoz

Chapter 5

Redesign of the Rim Jet

Utilising the DFMA tools presented by Boothroyd, key elements suitable for this project were identified and chosen. For the initial phase, manufacturing techniques and materials offered by SKF were inspected and evaluated. To begin the DFMA procedure, the design by Mũnoz was inspected, analysed and evaluated. Problematic areas were identified and assessed in relation to other parts of the design. The Rim Jet was then broken-down into its individual parts and modified for improvements, both within each part, as well as improving the complete system. During this phase an array of areas had to be considered, starting with DFM and DFA as well as modular aspects and functionality related to the performance of the engine. The final design aims to simplify and optimise the Rim Jet for an initial prototype that is simpler, faster and cheaper to make.

5.1 Tools chosen for the Rim Jet project

DFMA can be implemented with varying degrees on a project or product. Boothroyd segments the method into three main areas. First an initial design phase, secondly, Designing for Manual Assembly and finally, Design for Manufacture depending on what manufacturing method that is intended for each individual part. For this project, certain areas within each segment has been identified as applicable and is presented as follows.

5.1.1 Selection of Materials and Processes

Boothroyd presents an issue that, when conceiving new parts, engineers often tend to only consider the materials and tools they are most familiar with. This might exclude methods that could prove more economic. Therefore, a first step is to identify all possible manufacturing techniques available. Within this project, the manufacturing methods and techniques are limited to the tools available in the workshop at SKF. Following is a list of available manufacturing techniques:

- Manual and CNC Turning
- Manual and CNC Milling
- Soldering
- Welding
- 3D printing (plastic)

These were all presented and inspected during a meeting in their facility in Gothenburg. Choosing the right tool for manufacturing is essential when designing the individual parts. Unnecessary shapes and geometrical forms can result in complicated production steps, all resulting in a higher final cost. Impossible shapes or unreachable tolerances are also areas that have to be considered when deciding on a manufacturing method and part design.

The second area of consideration presented by Boothroyd is the material selection. Different methods of selecting materials are presented, however for implementation on this initial prototype, material selection will be generalised to Stainless steal and Aluminium as this is the materials offered by SKF.

5.1.2 Design for Assembly

DFMA can be split up into two segments, Design for Assembly and Design for Manufacure. There is a wide array of aspects that have to be considered when designing for assembly. The core goal of DFA is to minimise the number of parts and the time needed for each operation during assembly. This can be related to eliminating adjustments, designing self aligning- and self locating parts, minimise the need for reorientation during assembly and other time consuming operations. Boothroyd provides illustrations and guidelines on design solutions to improve the assembly methods and structures. For a prototype project like the Rim Jet, the lack of a production line makes comparing assembly time and production costs difficult. However, future changes and upgrades to the Rim Jet will benefit from a simple and easy assembly process as well as improved quality and modularity.

5.1.3 Design for Manufacture

When assessing the manufacturing aspect of a product, the focus is aimed toward the methods, tools and procedures needed to produce the individual components that makes up a larger assembly. As discussed earlier, deciding on the optimal material to use for each individual part is a fundamental part of DFM. Nevertheless, when evaluating a material for selection, the manufacturing aspects should be taken into consideration. For example, choosing a cheaper material could result in a more costly manufacturing process. This is because unsuitable or low quality materials might require special tools or equipment to process, as well as potentially increasing unnecessary manufacture waste.

Bothroyd provides a comprehensive guide on how to design depending on the chosen manufacturing method. Within this project a primary focus will be on the chapter "Design for Machining" as this is the main production technique at SKF.

5.2 Design Overview of the Rim Jet

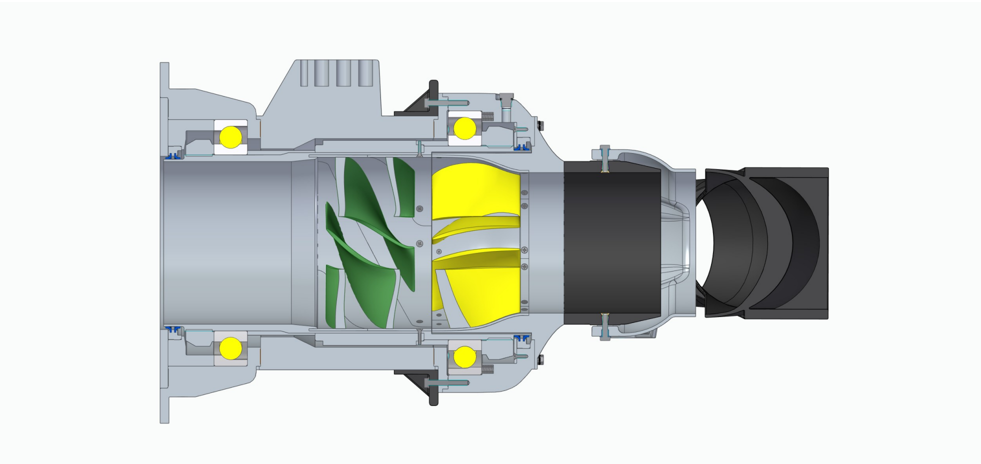

Figure 5.1: Section view of the complete Rim Jet assembly by Munoz

Displayed in Figure 5.1 is the complete engine as designed by Munoz. The assembly consists of 18 individual non-standard parts that require manufacturing. For this thesis the Outlet Tube, Steering Nozzle, Reversing Bucket Support and Reverse Bucket have been excluded to simplify manufacturing of the prototype. This decision reduces the total number of custom parts to 14 before design modifications.

5.2.1 Problematic Areas

After a consultancy meeting with Ulf Mansnerus from SSPA, who was involved with the project in the beginning of 2014, problem areas regarding fluid dynamics and Rotor and Stator positions were identified from the initial design done by Munoz. Next, a detailed examination of each individual part as well as their respective interactions to other parts was examined using a perspective of optimising manufacturing, assembly, disassembly and modularity. This was done to prioritise and evaluate necessary changes that could affect other parts of the design. Following are illustrations and descriptions of potential problem areas both in relation to performance as well as production, assembly and modularity.

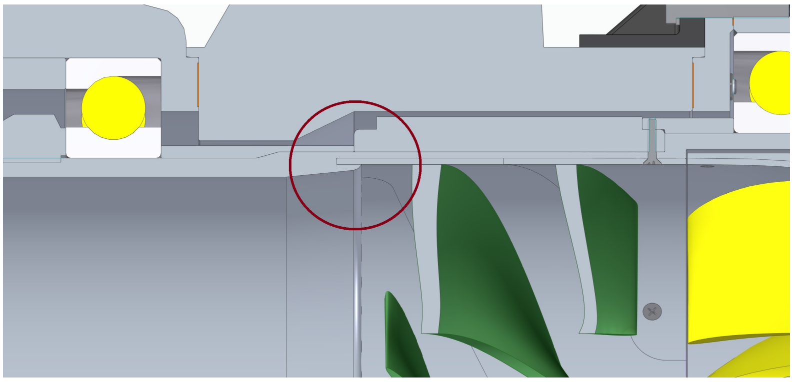

Figure 5.2: Circle indicates the slot for the Rotor blades

One critical manufacturing issue identified on the Rotor tube, se Figure 5.2, is a slot designed for inserting the rotor blades to. A slot this deep would not be possible to manufacture with a CNC lathe from a single piece of metal. Munoz tried to so solve this by splitting the rotor tube in two sections, manufacturing each separately and then welding them together in the middle. However, with a rotational speed of approximately 4000rpm any tolerance deviations regarding centricity could result in vibrations within the engine and with time, fatigue and stress, could result in malfunction. The individual rotor blades would also be complicated to insert together both during first assembly, during production, as well as later during design changes, modifications, upgrades or reparations.

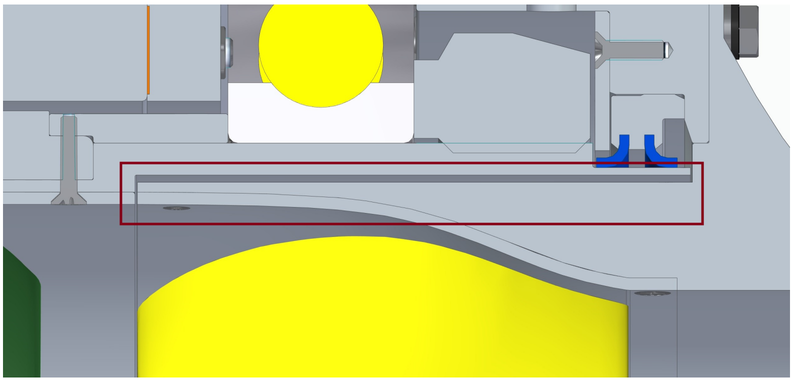

Figure 5.3: Rectangle indicates the problematic area between Rotor tube and Stator housing.

Another issue on the initial design is the gap between the Rotor tube and the Stator housing, se Figure 5.3. When the rotor spins and pushes water backwards through the engine pressure builds up downstream. When the diameter shrinks during the stator phase pressure builds even further. Sand and other debris within the water will be pressed outwards because of the centrifugal force as well as the pressure within. There is therefore a potential risk that the gap between the rotating Rotor tube and the static Stator housing will be clogged with sand and particles, diminishing the performance of the engine and its life expectancy. This gap also requires high tolerances for both the Rotor tube as well as the Stator housing to ensure free rotation from one another and precision processes like this require more time and expensive tools.

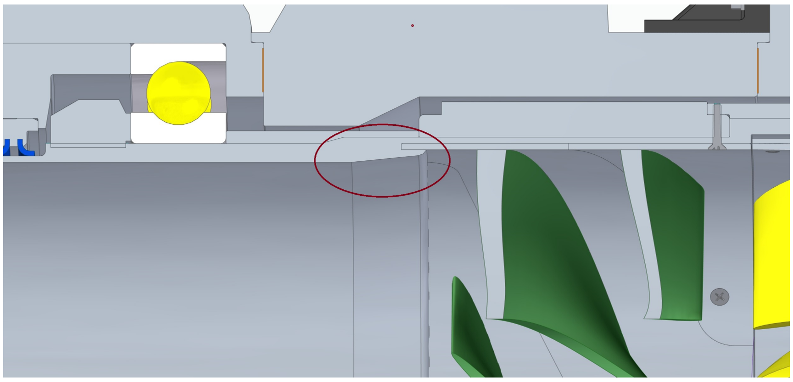

Figure 5.4: Circle indicates the area change between inlet and Rotor blades

When designing a jet propulsion system it is essential to go from a larger inlet diameter and compressing the fluid downstream to generate a higher velocity. Area changes need to be correct to not generate wall turbulence and other issues that reduce efficiency and performance. One such issue was found between the beginning of the rotor tube and the transition to the rotor blade as shown in Figure 5.4. The area change would most probably result in a vacuum right after the edge and induce a turbulent flow that would decrease the efficiency of the engine. The change could also have effects on the rotor blades causing vibrations or loss in efficiency.

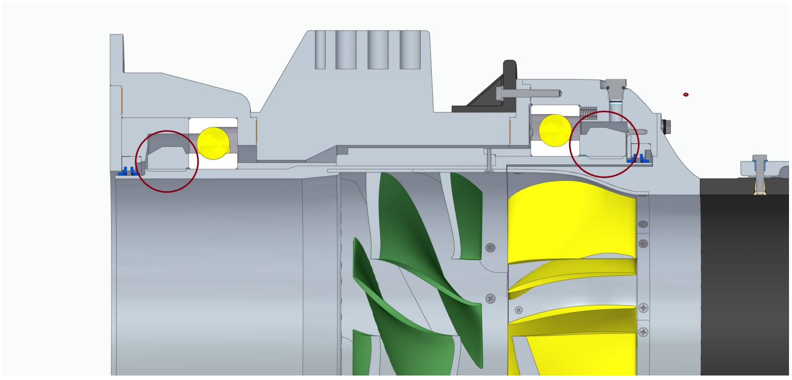

Figure 5.5: Current Rotor Tube

Reducing part count is essential for DFMA and identifying unnecessary parts before production is key to reducing development costs. In this design, the two Precision lock nuts, se Figure 5.5 was identified as not providing any value to the design. The purpose of the nuts was to lock the bearings in to place on the rotor tube. However, that is already accomplished by the bearing housing RS (Rotor Side) as well as bearing housing SS (Stator Side) on each side of the engine that forces the bearings in to place with the pre tensioning springs on the SS side as well as the bearing configuration chosen by Mũnoz.

5.2.2 Analysis and evaluation of the initial Rim Jet design

Applying DFMA to the Rim Jet design in practice requires a decomposition of the Rim Jet to its constituent parts and a examination of them in respect to other components. Normally when implementing DFMA and in particular DFA, an assessment of assembly time as well as specific cost for each individual part are taken into consideration. For this project however this is not an option. Instead, an evaluation of the number of parts and their connections to other parts is assessed. The "Number of interfaces" is derived by examining each part individually and determining the number of places were the part physically interacts with other parts. Adding to this, a weighting method depending on the expected cost relative to other parts is conducted to evaluate if changes made will reduce the overall cost of the parts needed and not only the number of parts. The weight is ranked with L for Low, M for Medium and H for high. The ranking is set depending on several elements, material cost, weight, production time as well as how hard or easy it is for SSRS to acquire each part. The parts are listed in order of assembly and the engine will act as the base platform.

Table 5.1: Analysis before design changes

Part number	Part name	Number of parts	Number of interfaces	Cost (L/M/H)	W_n	W_p
1	Engine	1	3	H	9	27
2	Tube					
2.1	Rotor tube	1	17	M	3	51
2.2	Bearing possitioner RS	1	2	M	3	6
2.3	Bearing possitioner SS	1	3	M	3	9
2.4	Rotor blades	4	8	H	9	72
2.5	Bot M4 L18	8	32	L	1	32
3	Connecting					
3.1	Connector	1	24	M	3	72
3.2	Bearing Housing RS	1	28	H	9	252
3.3	Pass throgh bolts	12	24	L	1	24
3.4	Nut M6	12	24	L	1	24
4	Rotor side of engine					
4.1	Bearing RS	1	5	H	9	45
4.2	Precition nut RS	1	2	M	3	6
4.3	Sealing positioner RS	1	4	M	3	12
4.4	Sealing RS	1	2	H	9	18
4.5	Cover plate RS	1	14	M	3	42
4.6	Bots M6 L30	12	24	L	1	24
5	Stator side of engine					
5.1	Bearing SS	1	33	H	9	297
5.2	Precition nut SS	1	2	M	3	6
6	Bearing Housing					
6.1	Bearing Housing SS	1	72	H	9	648
6.2	Springs	30	60	L	1	60
6.3	Sealing SS	1	2	H	9	18
6.4	Cover Plate SS	1	13	M	3	39
6.5	Bolt M4 L14	12	24	L	1	24
6.6	Gortex vent	1	1	L	1	1
7	Stator side of engine 2					
7.1	Bolt M6 L45	12	24	L	1	24
8	Stator					
8.1	Stator Blade Housing	1	43	M	3	129
8.2	Stator Blades	6	30	H	9	270
8.3	Bolt M3 L4	12	24	L	1	24
8.4	Bolt M4 L12	12	24	L	1	24
8.5	Bolt M6 L14	12	24	L	1	24
Total		162	592			2304

$$W_p = W_n * N_n \tag{5.1}$$

Where W_p = Weighted value, W_n = The Weight (1/3/9) and N_n = Number of parts

It is difficult to draw any initial conclusions from Table 5.1. The aim is to reduce the total value of each segment to optimise the design as a reduced number of parts will potentially reduce the total cost of the Rim Jet and a reduction in interfaces could reduce assembly time as well. Using a weighted system makes it possible to rank a simple change to a complicated and costly part higher then a small change to a simpler part. It should also be observed that the assembly structure is divided into eight sections, with each section being a subsystem assembled to then be attached to the main assembly.

5.3 Design Modifications of the Rim Jet

Following is a decomposition of all parts presented in the work by Mũnoz. Connected to every part is a description of issues regarding DFMA and the changes made. For a detailed comparison see blueprints in Appendix A.

5.3.1 Rotor Tube

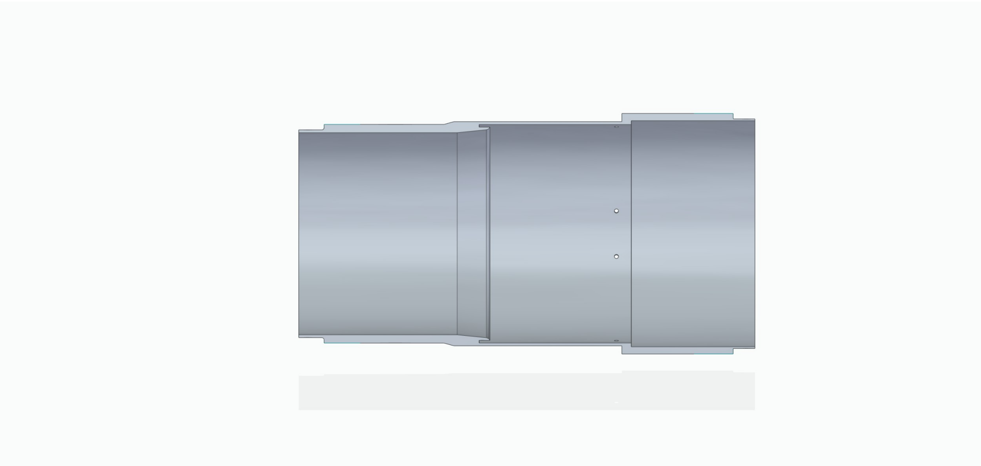

Figure 5.6: Section view of the Rotor Tube designed by Mũnoz

The purpose of the rotor tube is to transfer the rotational force from the rim motor to the rotor blades. It slides in and fits inside the rim of the motor and is fixated with bolts. The rotor blades slide in from the right in Figure 5.6 and are fixated through bolts and a groove in the wall of the tube. The tube has outside threads for the bearing holders as well as high tolerance surfaces where the seals slide on.

Modifications

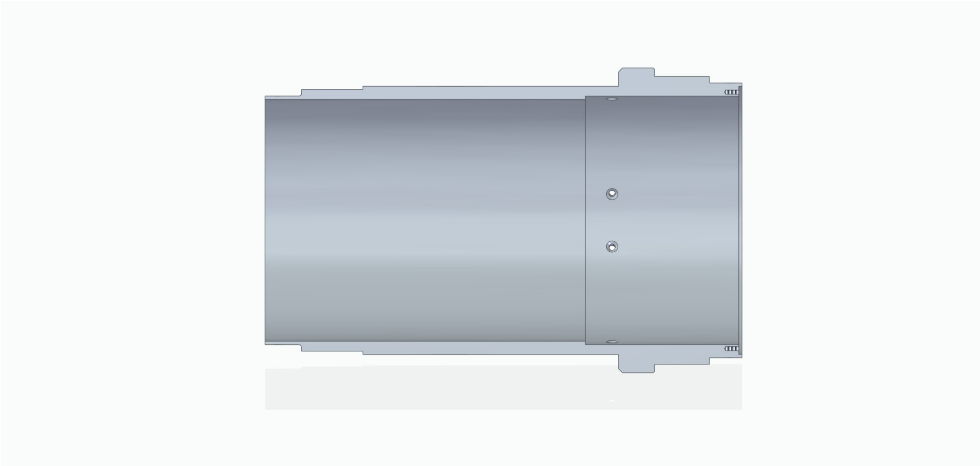

Figure 5.7: Current Rotor Tube

A number of modifications were made to the rotor tube to fit the improved design. Foremost, the complicated axial slot for the rotor blades have been removed. Together with the removing of the rotor-slot, the diameter change at the same place has also been removed. Instead, now the tube has one fixed diameter from the inlet until it reaches the beginning of the stator blades. This change also made it possible to increase the thickness of the rotor tube wall around the engine-rotor. The rotor blades were also moved backwards, correcting the potential issue with sand and other particles travelling in between the rotor and the stator in the initial design. This change also improves the modularity of the engine where it now is easy to access and exchange both rotor or stator blade if damaged. For further changes see Figure 5.6 and Figure 5.7.

5.3.2 Bearing Housing RS

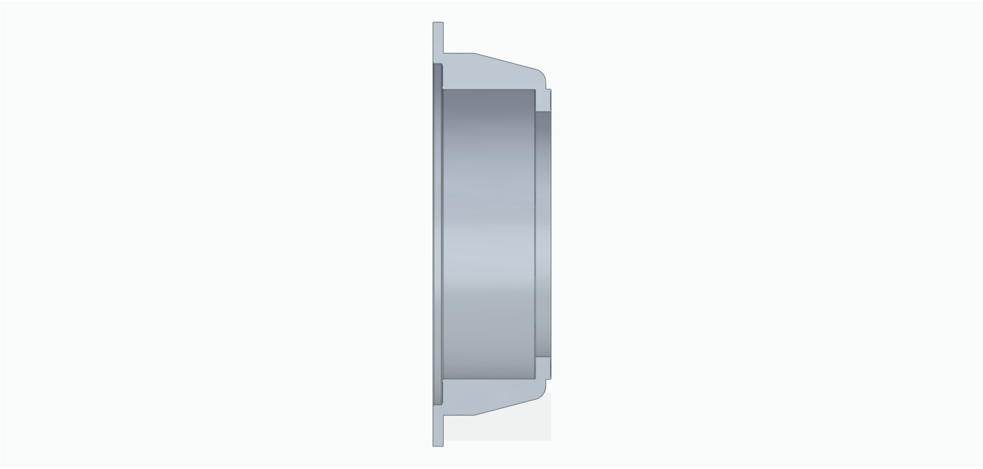

Figure 5.8: Section view of the Bearing Housing RS by Mũnoz

Connecting the engine to the rescue craft is the Bearing Housing RS. It also contains the Bearing Seat for the Front Bearing.

Modifications

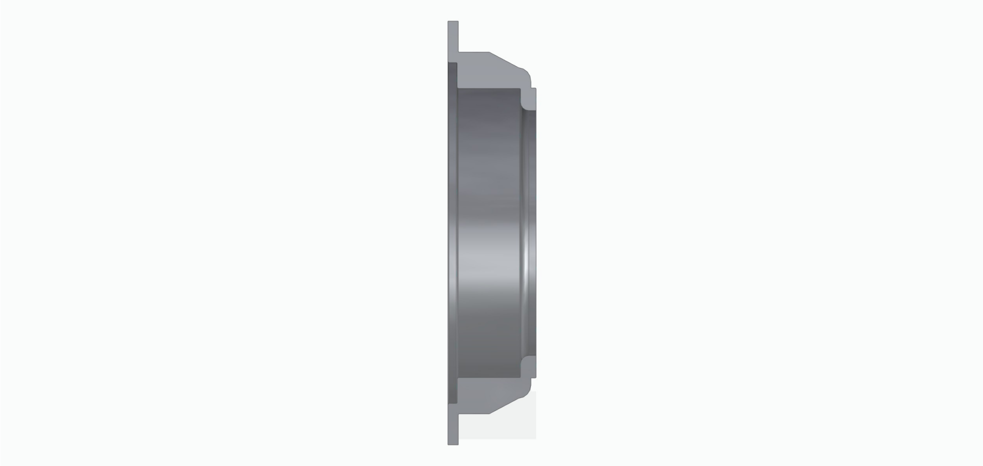

Figure 5.9: Current Bearing Housing RS

The overall design of the Bearing Housing RS has not changed substantially. The most notable change is the axial shortening of the part that reduces the weight of the piece from 28kg to 20kg. The holes for the pass through bolts have also been changed to threaded holes to simplify assembly when the bearing is inserted in its designated place. The gaskets have been removed from this initial prototype design to simplify both assembly and production. Instead a silicon compound is used in the prototype to ensure a complete seal when assembled. This type of sealant is cheaper and easier to apply to a prototype, however it is not as reliant as a toric joint and should be reevaluated for a potential future rim jet model.

5.3.3 Cover Plate RS

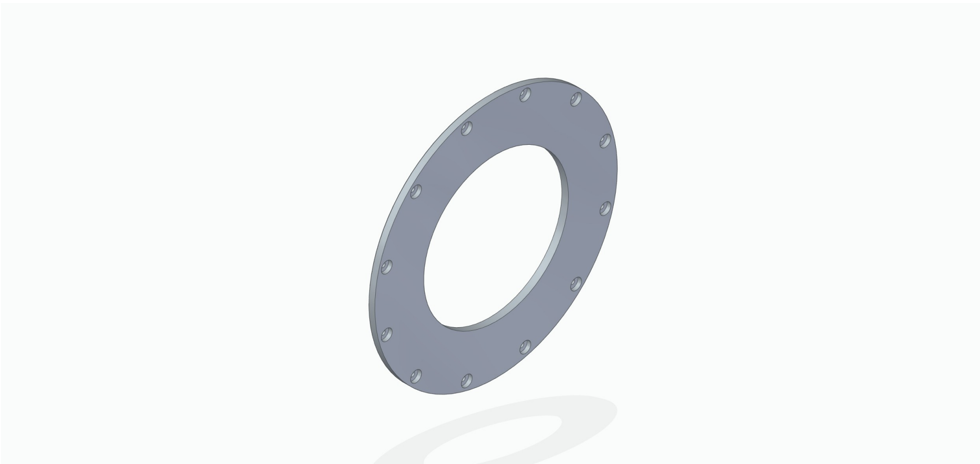

Figure 5.10: View of Cover Plate RS by Mũnoz

To lock the sealing positioner and bearing in place a cover plate is used, a simple round disk bolted to the bearing housing RS.

Modifications

Figure 5.11: Current Cover Plate RS

No drastic changes were made to the cover plate RS, some dimensions have been altered to fit the new design of the bearing housing RS.

5.3.4 Sealing Positioner RS

Figure 5.12: Section view of Sealing Positioner RS by Mũnoz

The seals used in this design are manufactured by Trelleborg. To hold the rotary seals in place a sealing positioner is placed within the bearing housing and fixated in place by the cover plate.

Modifications

Figure 5.13: Section view of current Sealing Positioner RS

For the sealing positioner RS the axial length of the part was shortened to reduce weight. The material is also changed to aluminium as this piece will not endure heavy load. This reduces the weight from 5.4 kg to slightly below 1 kg. The overall functionality is not changed because of the dimension restrictions from the previously chosen rotary seals.

5.3.5 Bearing Positioner RS

Figure 5.14: View of Bearing Possitioner RS by Mũnoz

Transferring the axial bearing forces from the engine to the hull means using a bearing positioner on the right side of the bearing. It slides on from the left after the rotor tube has been attached to the motor rim.

Modifications

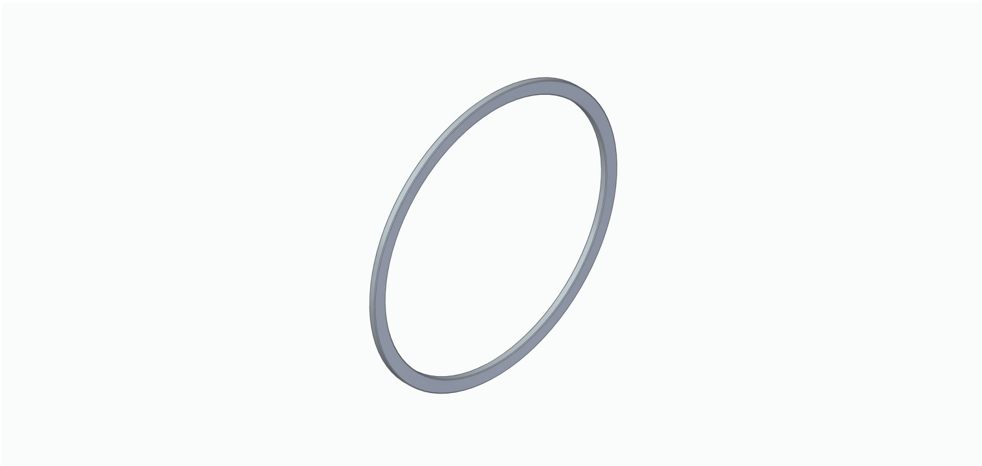

Figure 5.15: The new Rotor Extention

To ensure simplicity for production the bearing positioner RS was renamed the rotor extension 5.15. With the changes on the Rotor Tube a lighter and simpler part was designed to fulfil the same purpose.

5.3.6 Rotor Blades

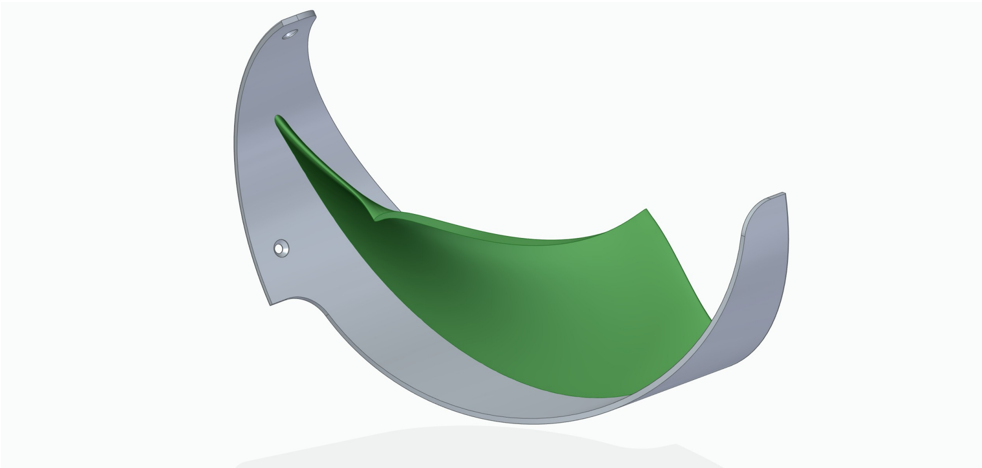

Figure 5.16: Rotor Blades by Mũnoz

Converting the rotational momentum from the engine to the water, a collection of blades are used. These are all individually made on separate sheets and then placed within the tube and fastened with bolts radially through the rotor tube.

Modifications

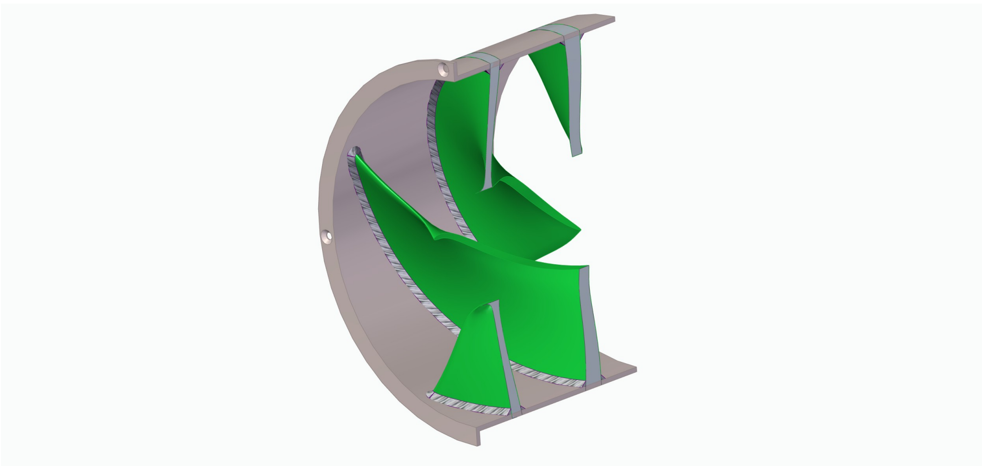

Figure 5.17: Section view of current Rotor Blades

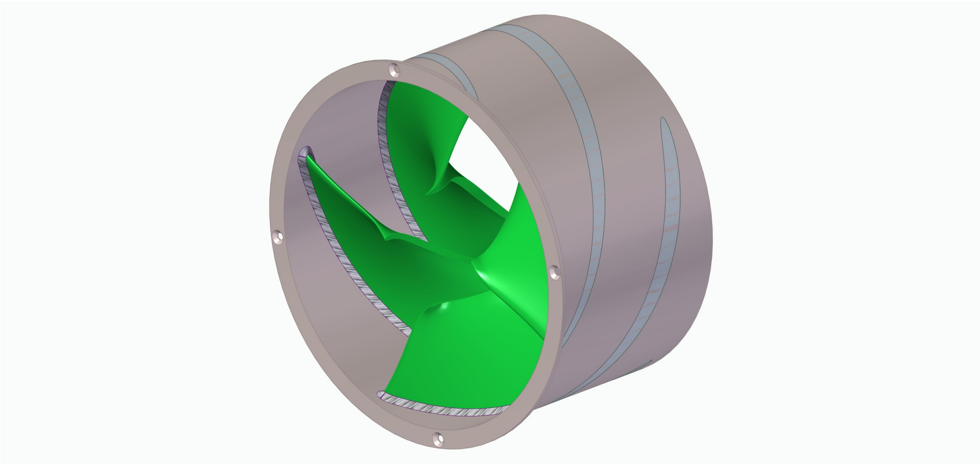

Figure 5.18: View of the complete Rotor Blades

The rotor blade is, together with the stator blade, the most complex part of the engine and choosing a suitable production technique is difficult. Instead of making individual blades that slide into the engine separately, a 3D printing solution is used where the blade and tube is made in one single piece. Initially they will be made from durable plastics and if needed treated with a cover of fiberglass to strengthen the blades. In the long term there are options such as composite 3D-printing as well as metal 3D-printing that might be suitable, although the later would be more costly. It is fixated with bolts going through the flange at the rear end of the rotor tube to ease installation and maintenance.

5.3.7 Bearing Positioner SS

Figure 5.19: Bearing Possitioner SS by Mũnoz

On the opposite side of the motor is another bearing positioner, bearing positioner SS. It connects the axial bearing forces from one side of the engine to the other. This one is bolted with the same screws that are used to fixate the rotor blades.

Modifications

This part has been removed and instead it has been combined with the rotor tube as it fills no purpose to be a separate unit.

5.3.8 Connector

Figure 5.20: Section view of the Connector by Mũnoz

The connector has two main tasks, connecting the bearing housing SS to the engine and acting as a mounting ring for the reverse bucket.

Modifications

Figure 5.21: Section view of the current Connector

Slight dimensional modifications were made to the connector to reduce weight.

5.3.9 Bearing Housing SS

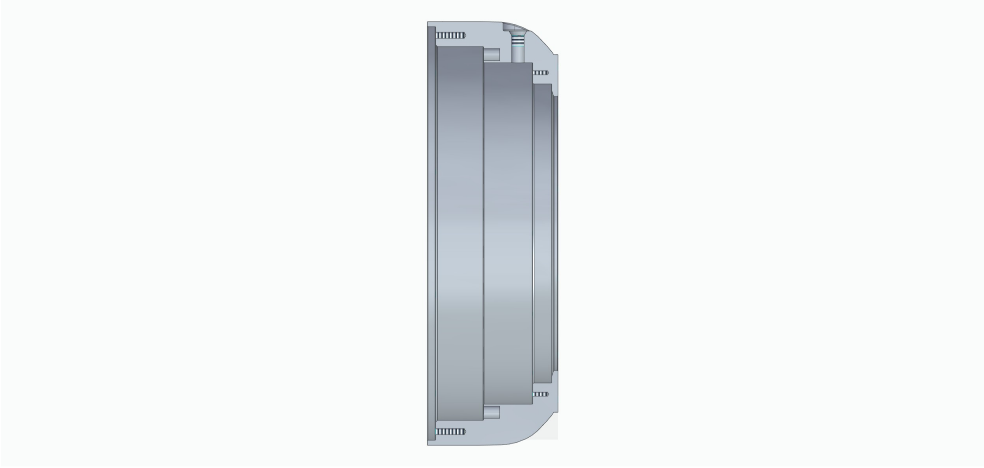

Figure 5.22: Section view of the Bearing Housing SS by Mũnoz

As previously explained the bearing housing is made to house the bearings and in this case also the rotary seal. For this side of the engine the housing is also equipped with springs to create a pre-tension on the bearings. A threaded hole on the top makes adding lubricating oil easy.

Modifications

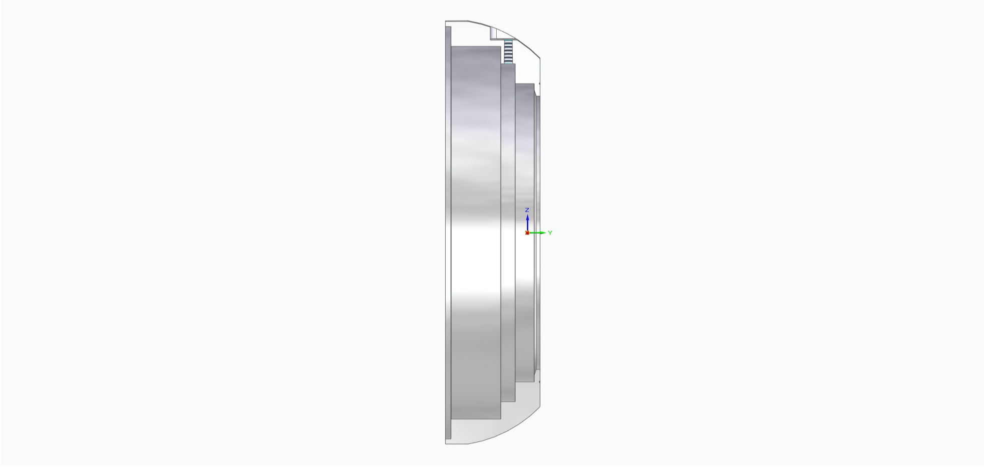

Figure 5.23: Section view of the current Bearing Housing SS

As with most major parts, the axial length have been reduced and hence also reduced the weight of the piece. The chosen material was changed to aluminium to further cut down on weight. As this part is subjected to lower amounts of force than its counter part, bearing housing RS, this change should not affect the strength and durability. Most other aspects of the part stayed the same. This relates to holes for connecting other parts, springs for bearing pre-tensioning, seal and bearing seats.

5.3.10 Cover Plate SS

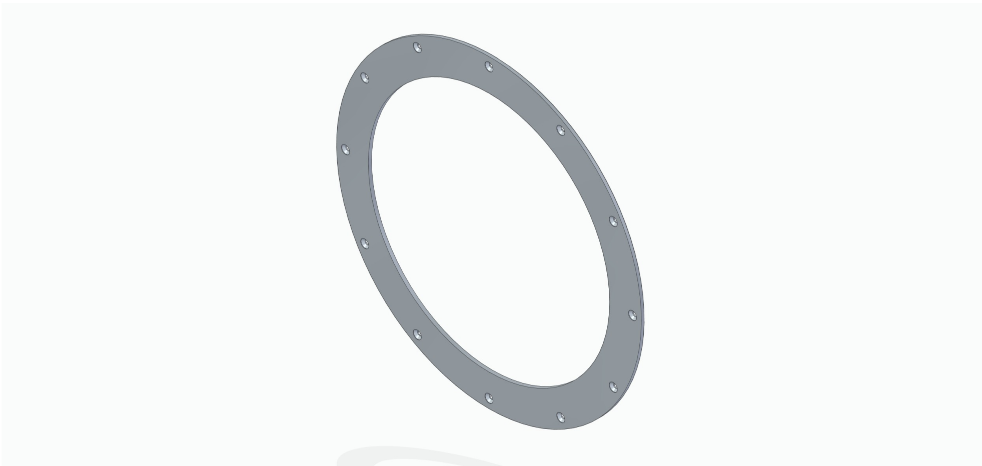

Figure 5.24: Cover Plate SS by Mũnoz

Locking the secondary rotary seal in place is the cover plate SS.

Modifications

Figure 5.25: Current Cover Plate SS

The primary change was the reduction of connecting holes to the bearing housing SS. This was done because there is no large forces involved and the purpouse of this part is to lock the rotary seal in place. Small dimensional changes were also made.

5.3.11 Stator Blade Housning

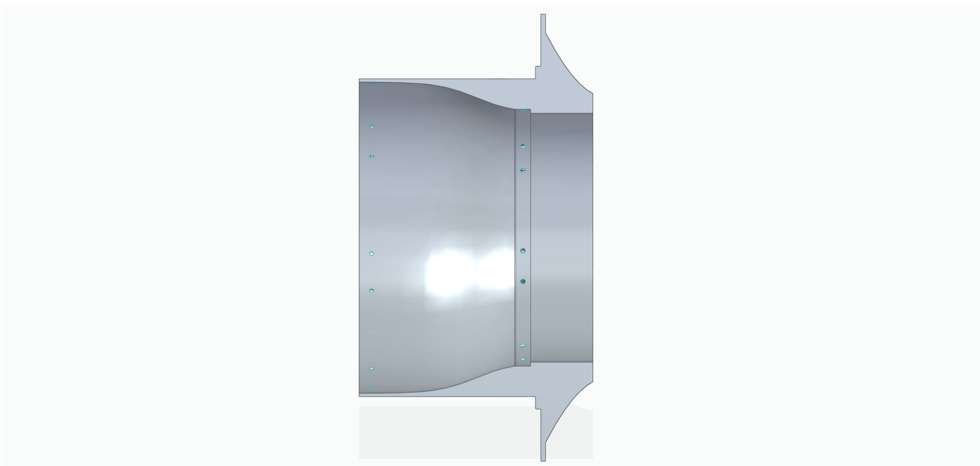

Figure 5.26: Section view of Stator Blade Housing by Mũnoz

The last part before the outlet nozzle is the stator blade housing. It connects to the bearing housing SS with bolts and tunnels the water to a smaller outlet area.

Modifications

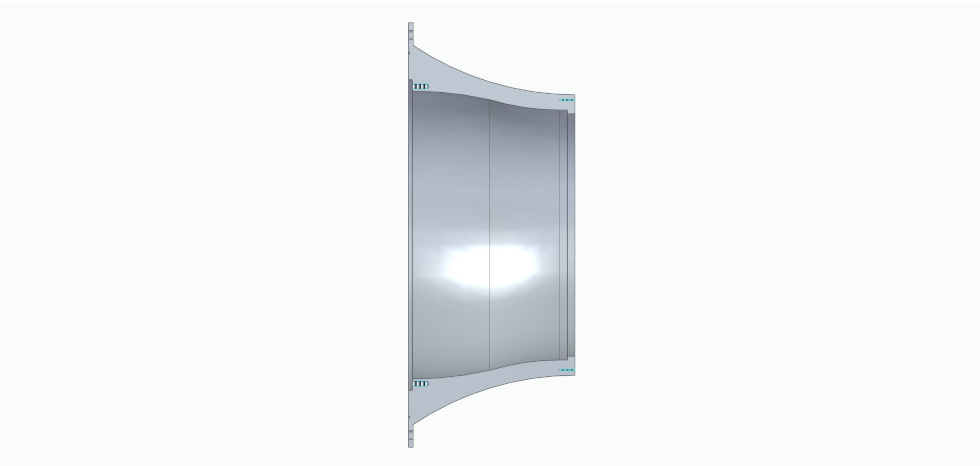

Figure 5.27: Section view of current Stator Blade Housing

Drastic changes were made to the stator blade housing to adapt to the new rotor tube design. The new design fits the Stator blades behind its connection to the bearing housing SS. The new design is significantly easier to manufacture and does not require as high tolerances as the previous. To lower the total height of the engine, the part was changed from stainless steal to aluminium. As this is a part that might wear out faster than others, a future design might change the back to stainless steal for a more reliable design.

5.3.12 Stator Blade

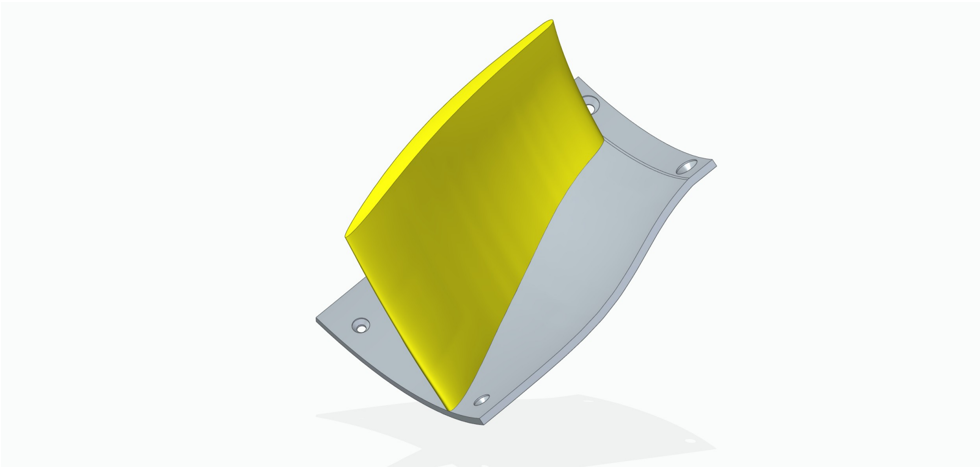

Figure 5.28: Stator Blade by Mũnoz

When exiting the rotor blades the water pushed through will have a rotational speed as well as the axial speed. To increase efficiency of the engine, this rotational speed is reversed back to axial by the stator. This, together with the diameter change from inlet to outlet is what constitutes a jet configuration. The six separate blades are made individually and fastened with four bolts for each blade to the stator housing.

Modifications

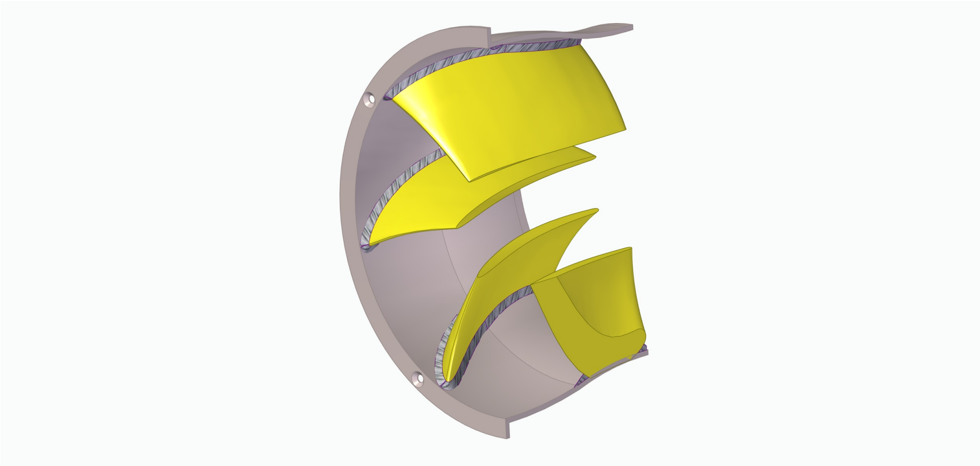

Figure 5.29: Section view of current Stator Blade

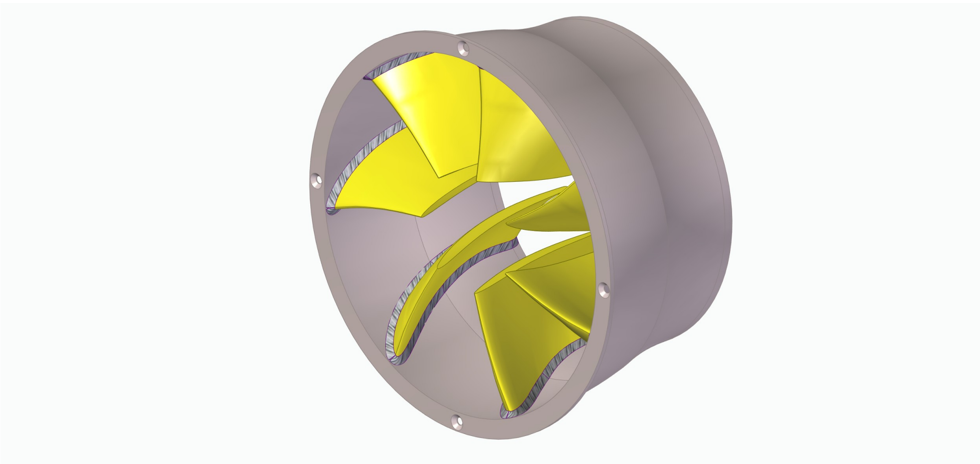

Figure 5.30: Complete view of current Stator Blade

The same changes made to the Rotor Blades was made to the stator blades. To ease manufacturing, installation and maintenance all of the blades are manufactured on the same tube that slides into place in the stator holder. It is fixated rotational and axially with bolts screwed axially on the flange at the inlet of the stator blade housing.

5.3.13 Pass Through Bolts

Figure 5.31: Pass through bolts designed by Mũnoz

Connecting both sides of the engine is the Pass Through Bolts, that runs through the engine and is locked with nuts from the Connector Side.

Modifications

Instead of manufacturing bolts, a threaded rod with a bolt on the end will be used to clamp the connector and the Bearing Housing RS around the engine-stator.

5.3.14 Standard parts

Following is the list of standard parts documented by Mũnoz for his design:

Part	Identification	Provider	Quantity
Angular Contact Ball Bearing	71940 ACD/HCP4A	SKF	1
Angular Contact Ball Bearing	71944 ACD HC	SKF	1
Precision Lock Nut	KMT 40	SKF	1
Precision Lock Nut	KMT 44	SKF	1
Rotary Seal (rotor side)	TJ D 1 B 1900 - T40 2 M	Trelleborg	1
Rotary Seal (stator side)	TJ D 1 B 2100 - T40 2 M	Trelleborg	1
Gasket	HiMod FlatSeal 10	Trelleborg	4
Goretex Vent	Poly Vent High Airflow PMF100585	Gore	1
O-ring	10x2mm	-	1
Spring	CSS 1.6x8x22	Lesjöfors	30
Bushing	PCMF 060808 E	SKF	2
Bushing	PCMF 081009.5 E	SKF	2
Metallic Threaded Insert	HITSERT 2 Type 09311060011	Böllhoff	2

Modifications

Most standard parts from the initial design are the same. One big change is the removal of the Precision Lock Nuts that was previously used to fixate the bearings on the Rotor Tube. After inspecting the bearing arrangement and functionality it was concluded that they were unnecessary for this application. This resulted in the removal of the thread on the Rotor Tube which made the Resulting Tube shorter and hence made the complete motor shorter. Other changes made was the removal of gaskets and toric joint to further simplify the parts and later assembly. Since this is a first prototype sealing glue will be used instead and learning from future testing will determine where gaskets and O-rings are necessary.

Part	Identification	Provider	Quantity
Angular Contact Ball Bearing	71940 ACD/HCP4A	SKF	1
Angular Contact Ball Bearing	71944 ACD HC	SKF	1
Precision Lock Nut	**KMT 40**	**SKF**	**0**
Precision Lock Nut	**KMT 44**	**SKF**	**0**
Rotary Seal (rotor side)	TJ D 1 B 1900 - T40 2 M	Trelleborg	1
Rotary Seal (stator side)	TJ D 1 B 2100 - T40 2 M	Trelleborg	1
Gasket	**HiMod FlatSeal 10**	**Trelleborg**	**0**
Goretex Vent	Poly Vent High Airflow PMF100585	Gore	1
O-ring	**10x2mm**	**-**	**0**
Spring	CSS 1.6x8x22	Lesjöfors	30
Bushing	PCMF 060808 E	SKF	2
Bushing	PCMF 081009.5 E	SKF	2
Metallic Threaded Insert	HITSERT 2 Type 09311060011	Böllhoff	2

5.4 Modularity

An array of modifications were made to enhance the modularity of the Rim Jet. Most prominent is the change to the rotor and stator blades that simplified changing of said parts. Because of the switch to one solid tube with blades for both rotor and stator it is a simple task to create variations of rotor and stator blades for preliminary testing and later to change blades during operations. Depending on the shape and blade configuration, different characteristics can be enhanced in the motor. As of now the blades in the design are shaped in a similar way as for a regular pumping house. One issue still relating to that is the lack of head rise delivered from the engine to give required bull-board thrust. With this modular design an array of shapes can be designed, manufactured and tested with ease without changing other components.

5.5 Service and Maintenance

Modularity ties closely together with Service and Maintenance where a modular design always is easier to maintain. With the reduction of individual parts, together with lighter materials and a modular construction, time spent conducting service and maintenance is kept to a minimum. An advantage over regular water jets is that an electrical solution uses less moving parts. For the prototype design there are two bearings and two rotary seals that need inspection after a defined service interval as well as ocular inspection of the blades. A combustion engine relies on more moving parts to work properly and because of the vibrating nature of the engine, faults in the system can more easily occur.

5.6 Final Prototype Design

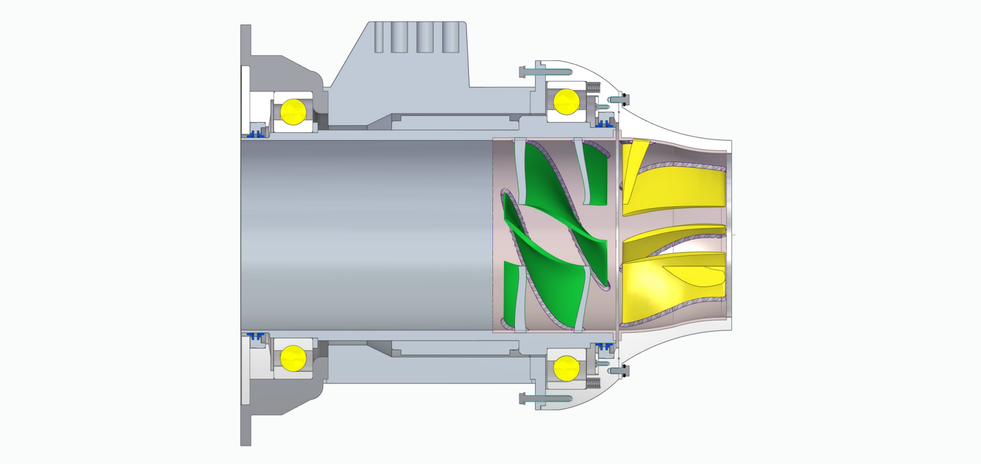

Figure 5.32: Final Rim Jet design feasible for production

Through utilising DFMA, a wide array of changes have been made to the Rim Jet design. The number of unique custom parts have been reduced from 14 to 11 including the 3D printed Rotor and Stator Blades. The total weight of the engine have also been reduced from 181kg to 133kg and problem areas have been dealt with. The resulting design is easy and affordable to manufacture, assemble, test, service and repair. Further optimisation regarding strength to weight ratio and quick locking mechanisms for assembly related to service and maintenance is reserved for future work.

5.6.1 Comparison of Initial Design to New Design Using DFMA evaluation

To evaluate the changes made to the Rim Jet a comparison of the old and new design is conducted. Using the same principles as previously the number of parts and connections are measured. Using equation 5.1 the weight is added to each component.

Table 5.2: Analysis after design changes

Part number	Part name	Number of parts	Number of interfaces	Cost (L/M/H)	Wheight	Wheighted
1	Engine	1	3	H	9	27
2	Connectors					
2.1	Bearing Housing RS	1	28	H	9	252
2.2	Connector	1	24	M	3	72
2.3	Pass throgh bolts	12	24	L	1	24
3	Tube					
3.1	Rotor tube	1	11	M	3	33
3.2	Bot M4 L18	8	16	L	1	16
3.3	Rotor blades	1	5	H	9	45
3.4	Bot M4 L12	4	8	L	1	8
4	Bearing Housing					
4.1	Bearing Housing SS	1	64	H	9	576
4.2	Springs	30	60	L	1	60
4.3	Sealing SS	1	2	H	9	18
4.4	Cover Plate SS	1	5	M	3	15
4.5	Bolt M4 L12	4	8	L	1	8
4.6	Gortex vent	1	1	L	1	1
4.7	Bearing SS	1	32	H	9	288
4.8	Bolt M6 L45	12	24	L	1	24
5	Rotor side of engine					
5.1	Rotor_extention	1	2	M	3	6
5.2	Bearing RS	1	4	H	9	36
5.3	Sealing positioner RS	1	4	M	3	12
5.4	Sealing RS	1	2	H	9	18
5.5	Cover plate RS	1	14	M	3	42
5.6	Bots M6 L30	12	24	L	1	24
6	Stator					
6.1	Stator Blade Housing	1	17	M	3	51
6.2	Stator Blades	1	5	H	9	45
6.3	Bolt M6 L14	12	24	L	1	24
6.4	Bot M4 L12	4	8	L	1	8
Total before changes		162	592			2304
Total after changes		115	419			1733
Reduction		-47	-173			-571
Reduction in %		29%	29%			25%

When comparing the results from the analysis before design changes to the results after changes in Table 5.2 it is evident that there has been a decrease across the board. Most prominently is the decrease in number of parts for the complete Rim Jet, a big change in both the number of interfaces as well as a reduction in weight is a clear indication of the improvements made. A second big change is the structure of the assembly with six sub assembly stages instead of eight that will improve the assembly process.

Chapter 6

Production

When manufacturing a prototype, cost and time is essential. Especially for ventures that rely on the free help from other companies, it is of upmost importance to make sure that the required favours are within reasonable limits. At SKF they have a multitude of machines and tools to manufacture a wide array of products and parts, but some methods are more time and cost consuming than others. The following two methods discussed will be used in the making of the first prototype. They are both the most cost and time effective when producing one prototype unit. Other manufacturing methods such as casting could be used in the future when producing multiple units without the material spill generated by turning and milling. A more in depth review of the different manufacturing methods are presented in the work by Mũnoz (Munoz, 2020)

6.0.1 CNC Machining

Machining in any form is a material subtracting process. It means that material is removed from a block to create the desired shape. Today, CNC, or Computer Numerical Control is the most commonly used production method when creating both small and large amounts of a part, as it is more effective and enables a higher precision than a manually operated machine.

6.0.2 Additive Manufacturing

Additive manufacturing, or 3D printing as it is more commonly known as, is an effective way to produce complex parts in a relatively short amount of time compared to other manufacturing methods. The main premise of 3D printing is putting a 2D layer on top of another layer to generate a 3D dimensional object. There are a wide array of methods on how to achieve this and as the technology progresses, new materials and solutions will be available on the market.

6.0.3 External suppliers

The prototype includes some parts provided by external suppliers. The Bearings made by SKF will be installed by them during manufacturing of the non standard parts. The rotary seals produced by Trelleborg have been acquired and awaits installation. The Gore-Tex Vent by Gore as well as the Springs by Lesjöfors is still under acquisition. The bushings by SKF and Metallic Threaded Insert by Böllhoff are needed for the reverse bucket and steering nozzle and will be obtained when necessary.

6.0.4 Simplicity

A substantial part of the work done on this project was related to producing as few and as simple parts as possible, both for economical reasons as well as a practical. The aim was to design parts with simple features that would still meet all the requirements. For this reason many features of the initial design were changed to adapt to this mentality. Some of the most prominent issues in the beginning related to manufacturing were the slot for the rotor blade inside the rotor tube, se Figure 5.2 as well as the problematic rotor tube around the stator tube, se Figure 5.3. Other areas such as the complete removal of the precision lock nuts simplified the production of the rotor tube. I n this case the threads at a diameter of over 200mm is a problematic element to machine, especially when the thickness of the tube is limited. Also, the task of assembling the Precision Lock Nuts would most probably prove difficult both during first assembly as well as during future maintenance.

6.1 Assembly

Assuring that all parts can be produced is equally as important as it is to ensure that they can all be assembled in a easy and efficient procedure. This also effects future service and maintenance as a complicated assembly structure is time consuming and can result in errors when reassembling after disassembly.

Chapter 7

Calculations On the New Design

Thor Peter Andersen laid forth the calculations of speed and thrust estimation that the current design is based on. In his work(Andersen, 2014) he began with using Savitsky's method of thrust prediction to determine the needed thrust for the vessel in question (the rescue boat). An energy model was then used to create a overview of the water flow through the system and to calculate required input data for data simulated testing. It is at this stage where the required head rise of the pump is calculated, an essential parameter when designing the rotor- and stator blades. He then proceeded with a steady flow CFD simulation and finally a Transient Flow CFD of the pump. The results from his simulations were used to finalise the blade design for the pump and the complete concept. Within this thesis work a comparison with the rudimentary equations and results from Andersens work will be preformed to evaluate the current status of the Rescue vessel.

7.1 Calculations with Current Specifications and Comparisons

The current water jet design differs rather notably from the design proposed by Thor in his work. An array of changes have been done to the design, most notably the inlet diameter change to fit the engine provided by Marna. Furthermore, the existing engine is predicted to have a higher maximum rotational speed then required by SSRS and Andersens work did not account for the weight of the engine (approximately 130kg). Therefore it is essential to review the calculations and update with the current data of the water jet to adequately compare test results with theoretical results. For this work the methods and equations of thrust prediction and other essential calculations will follow the structure and procedures put fouth by Andersen. Comparisons to previous work will be conducted and explanations, future tests and changes to future designs will be conducted in the end of the chapter.

7.1.1 Thrust Prediction

As presented in the work by Andersen a thrust prediction is made using the Savitsky's method. The method provides an adequate estimation for planing vessels and in this case the rescue boat. From the start of this project the boat has been estimated to weigh 800kg when deployed, this still stands reasonably true as the hull as the boat is about 200kg, the engine weighs in at around 100kg, battery is estimated to weigh around 300kg and a person with all essential equipment weighs about 100kg. The extra 100kg is a reasonable buffer for excess weight or future modifications.

The results from the Savitsky's method is as follows

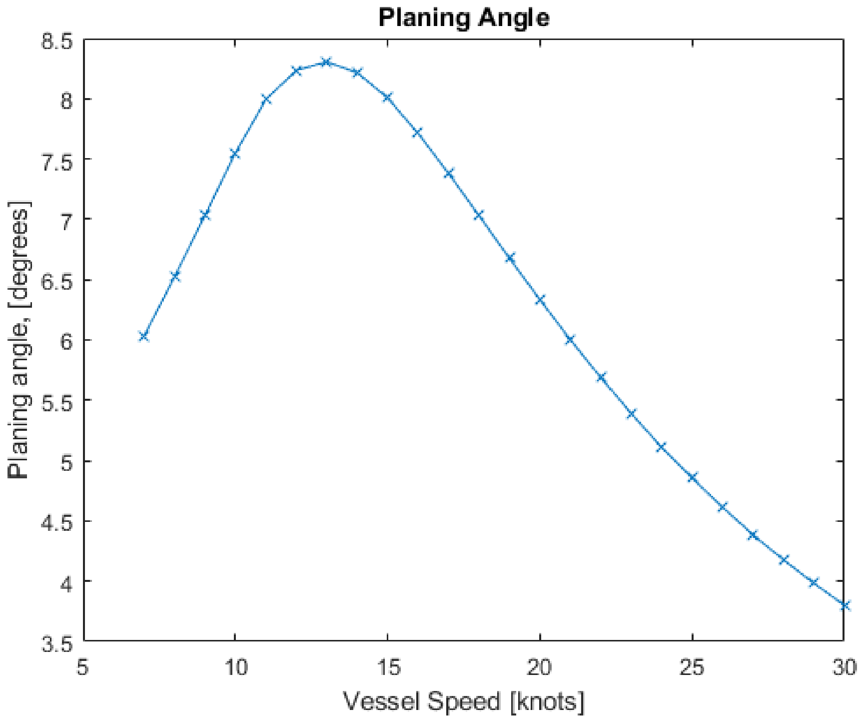

Figure 7.1: Planing angle plotted against the vessel speed

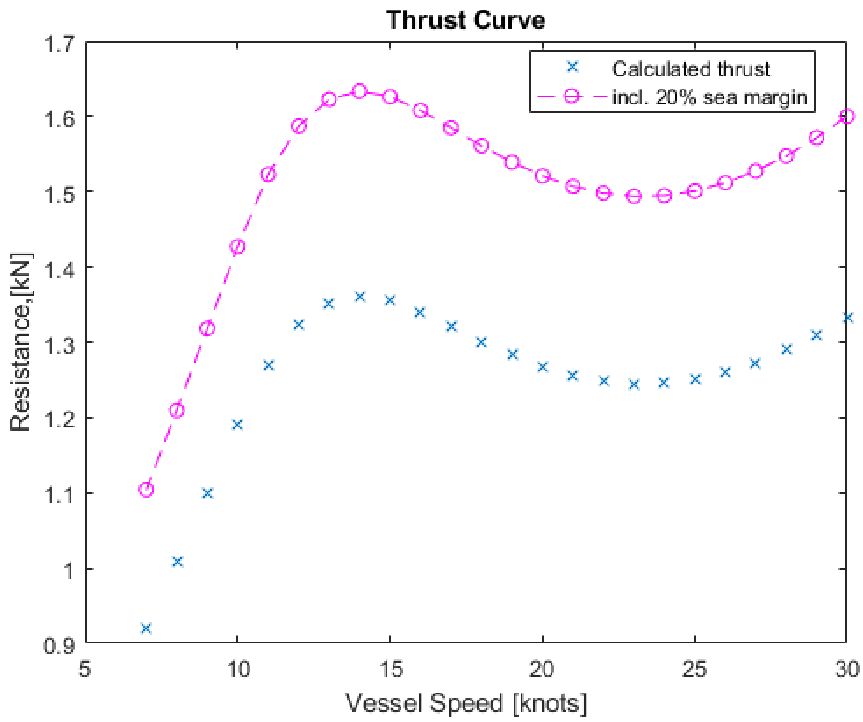

Figure 7.2: The thrust curve plotted against the vessel speed

7.1.2 Energy Model

For the second part a simple mathematical model is created to calculate the energy flow through the system. This part is essential to determine necessary requrements for the design of the rotor and stator blades. In Figure 7.3 a simple sketch of the pump is presented and used for the mathematical formulas.

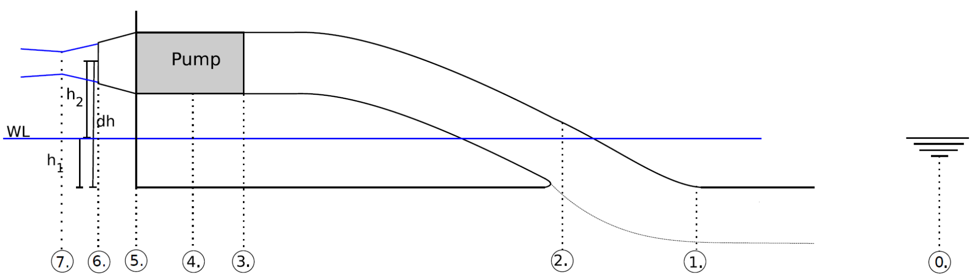

Figure 7.3: Illustration of the core elements of the pump

Following the premise of Figure 7.3 the folowing equations were derived

Using Matlab Andersen was then able to calculate the following results for the design depending on the speed of the vessel.

V_0	[knots]	0	19	20	21	22	23	24	25	26
T	[kNm]	4.00	1.54	1.52	1.51	1.50	1.49	1.49	1.50	1.51
H_{effect}	$[m]$	12.15	7.28	7.30	7.33	7.38	7.45	7.54	7.65	7.78
$h_{total\ loss}$	$[m]$	1.97	0.23	0.25	0.27	0.30	0.33	0.36	0.39	0.43
V_3	[m/s]	9.3	9.6	9.8	10.1	10.3	10.5	10.8	11.0	11.3
$\dot{Q}$	[kg/s]	0.28	0.29	0.29	0.30	0.31	0.31	0.32	0.33	0.34
$\dot{Q}_e$	[−]	1.07	1.11	1.13	1.16	1.18	1.21	1.24	1.27	1.30

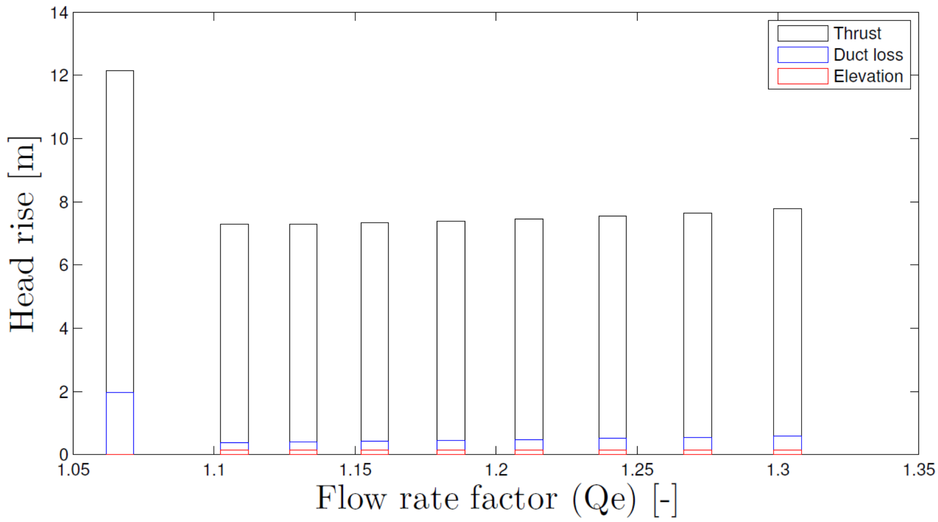

Figure 7.4: Presented in the figure are both the exact values from the energy model as well as the plotted head rise related to the flow rate factor

As of now these results are not accurate as they are based off the initial design of the pump, dimensions and values that have been changed for the prototype. Unfortunately, the inlet loss factor used in Andresens work is intellectual property by Rolls-Royce and is not retrievable as they are no longer connected to this project. However, the area of biggest concern to inlet duct factors are related to the bollard pull. Therefore, the solution in this case was to to try values that generate the same plot as in Andersens work, Figure 7.4, for the previous design and then use the same loss factor for the new design calculations. Approximate values and results from new calculations is displayed as follows

Table 7.1: Key results from the mathematical model on current design

V_0	$[knots]$	0	19	20	21	22	23	24	25	26
T	$[kNm]$	4.00	1.54	1.52	1.51	1.50	1.49	1.49	1.50	1.51
H_{effect}	$[m]$	12.22	6.94	6.95	6.97	7.01	7.07	7.14	7.23	7.34
$h_{totalloss}$	$[m]$	2.07	0.31	0.33	0.34	0.36	0.37	0.39	0.41	0.43
V_3	$[m/s]$	10.77	11.07	11.32	11.58	11.85	12.14	12.44	12.74	13.07
$\dot{Q}$	$[kg/s]$	0.29	0.30	0.30	0.31	0.32	0.33	0.33	0.34	0.35
$\dot{Q}_e$	$[-]$	1.14	1.17	1.20	1.23	1.26	1.29	1.32	1.35	1.39
$lossfactor_{aprox}$	$[-]$	0.35	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05

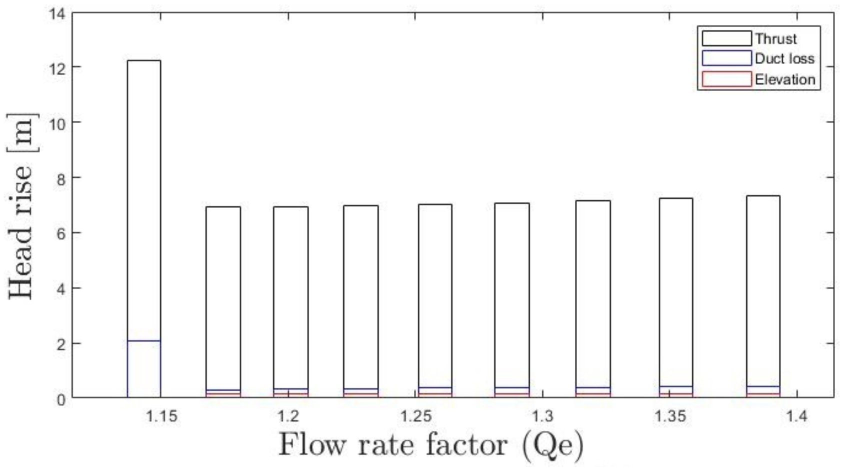

Figure 7.5: Plot specifying the head rise required to produce the necessary thrust for the current design

When comparing data from the old design to the current version some differences are noticeable whilst other values have stayed approximately the same. Because the outlet is till the same diameter as initially the required head rise H_{effect} is still the same to deliver the required Bollard pull T. However, to reach this, the velocity right before the rotor blades need to be increased from 9.3m/s to 10.77. This is also evident when viewing the volumetric flow rate $\dot{Q}$ and the normalised volume flow rate $\dot{Q}_e$ which have both seen an increase with the new design. This is all explained because of the decrease on the inlet diameter whilst remaining the same requirements for output. Because the vessel still needs the same amount of water pumped out of the stator but has a decreased inlet area the volume flow and in turn the inlet velocity needs to increase as to still generate the same output as previously.

There is a potential risk that the current blade design might not meet these new requirements on volume flow as they were designed and simulated with a larger inlet diameter. As stated in work on water jet pump performance by A. A. A. Sheha, M. Nasr, M. A. Hosien and E. M. Wahba the efficiency of a jet pump is extremely affected by the geometrical and operational parameters of the pump(Sheha et al., 2018). Therefore, this will have to be taken into consideration when testing the first prototype and could be a first area of research and modification when improving future designs.

Chapter 8

Battery and Power Solution

Until now the focus of this project in earlier thesis work has been on calculating and designing a working water jet. However one issue that has yet to be investigated is the power needed to propel the rescue craft.

8.1 Power Requirements

No demands has yet been set by the SSRS on the required operating time of the vessel. However, power is a essential part of the concept and for electric water crafts of any type it is one of the bigger issues when designing a functioning vessel.

Power requirements on the engine is stated by the documents provided by Marna. The following data is provided:

Engine specification	**Value**	**Unit**
Shaft nominal power	56	kW
Motor active power	64,2	kW
RMS Line Voltage	165	V
Speed nominal	4000	rpm
Torque	133	Nm

As of now the current Rescue Runners usually operates together with a larger mother ship when on missions. The rescue runner is mainly used to operate in difficult places were larger ships are unable to reach and the majority of the work is performed close to the main vessel. For the Rim Jet, prioritisation is therefore on performing with high capacity for a shorter duration of time then for a normal jetski or a larger ship as it will most often be transported to the location of the incident. A average mission time is estimated to around one hour by the SSRS, but if the Rescue Runner is transported by a lager vessel it is estimated that the Runner would be used for approximately 20 minutes. Knowing this is important as the weight of the battery significantly affects the performance of the boat.

Currently the boat is designed to allocate space for a battery of about 300kg. The Chief Operating Officer at X Shore, Oscar Fors, recommended the Deep Blue Battery BMW i3 after inspecting the specifications of the current engine. It weighs 278kg and has a capacity of 40.0kWh at 360V (Torqueedo, 2020). This is approximately the weight previously estimated to be needed for the Rescue boat. However, there is also currently the Deep Blue Battery BMW i8 that only weighs 97kg with a capacity of 10kWh at 355V (Torqueedo, 2020) reducing the weight of the vessel with 200kg. This is essential as it affects the inputs and outputs of the calculated thrust predictions.

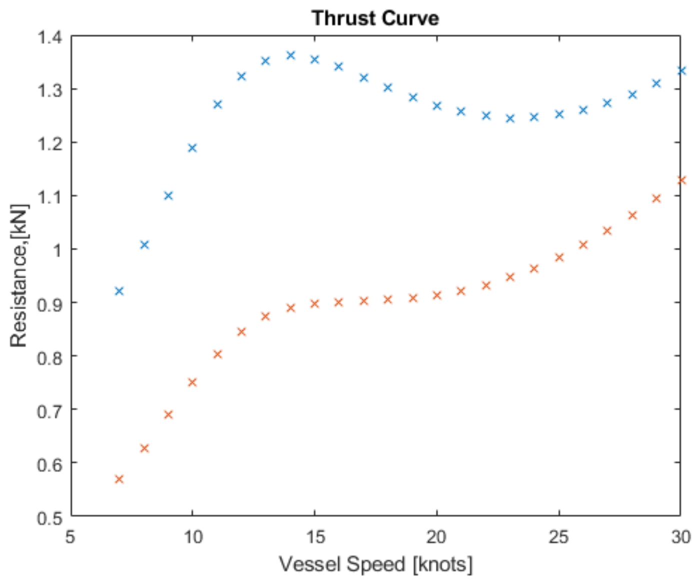

Figure 8.1: Thrust curve where the blue line shows the thrust needed when the vessel weighs a total of 800kg whilst the orange line is for a vessel at 600kg

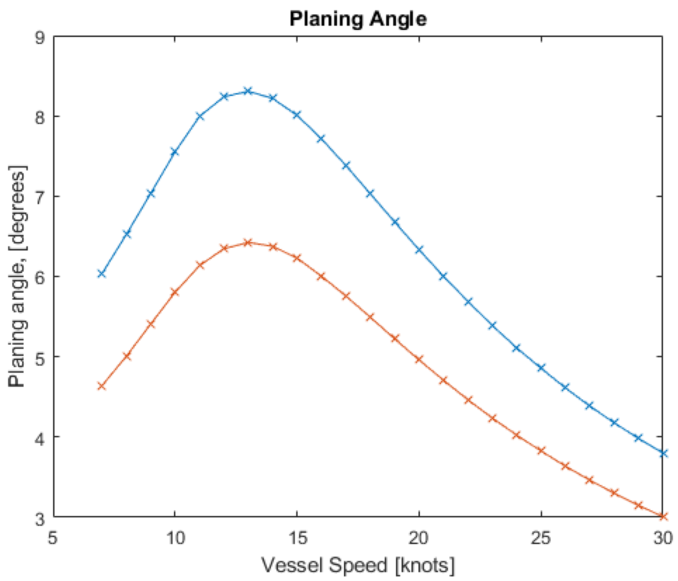

Figure 8.2: Planing angle where the blue line shows the thrust needed when the vessel weighs a total of 800kg whilst the orange line is for a vessel at 600kg

As can be seen in Figure 8.1 and Figure 8.2 the effects of the weight change is significant. Not only would a reducing in the weight of the craft result in less thrust needed to meet speed requirements it would also potentially benefit other areas such as weight distribution, manoeuvring, service and maintenance and compatibility with other crafts within SSRS when transporting the Rescue boat.

8.2 Suggestion

As of writing this paper new leaps in the battery industry are being made towards the commercial use of lithium–sulfur battery (Ny teknik, 2020). This could potentially lead to more efficient and lighter battery solutions in the near future and should be taken into considerations as the project moves forward after this paper has been published.

However, to begin practical testing of the design an initial solution is needed. SSRS has relationships with both Alelion (Alelion, 2020) and MicroPower Lionova (MicroPower Lionova, 2020). Therefore a collaboration to produce a fitting battery solution could be an option. Both of these companies makes custom battery solutions and therefore requirements on how much power is needed for the Rescue boat have to be made. From the specifications it is known that the engine needs approximately 64kW. It is estimated that the vessel will have to operate at a minimum of 20 minutes up to one hour, therefore a average operating time of 45 minutes is deemed reasonable.

Energy per kilo battery is essential for any battery driven vessel and using the examples from the Deep Blue Battery BMW i3 as well as i8, which are a commercial alternatives, a estimate of the kWh/kg can be calculated. The battery from BMW is designed to output approximately 360V, however our engine is designed for 165V. Therefore the battery output for the current engine will, at maximum load, only consume approximately half of the charge per time unit as it would if it was designed for 360V. Hence, for this application it could be estimated that the BMW battery's would deliver double their specified ampere hours. With this information and some simple calculations the following data is generated:

Table 8.1: Key results from the mathematical model on current design

Battery type	voltage [V]	Specified capacity [kWh]	Capacity [kWh] at 165V	Weight	Capacity/kg at 165V [kWh/kg]
BMW i3	360	40	≈ 80	278	0.28
BMW i8	355	10	≈ 20	97	0.21

Deriving from this data a rough estimation yields that a current commercial solution for the rim jet application will have a capacity at approximately 0.24 kWh/kg. With the requirement for a operational time at 45min and an active power consumption of 64.2kW rudimentary calculation gives that a battery with a weight of approximately 200kg wold be sufficient for the Rescue boat. Reducing the battery size with 100kg compared to the previously assumed 300kg battery would both save space on the vessel as well as deliver benefits described earlier. The battery installed needs to have a capacity of approximately 50kWh to meet the operation time requirements, and with the commercial options as a benchmark it would not be unexpected to reduce the weight further as batteries become lighter and more efficient in the future.

Chapter 9

System Integration

A crucial part of proceeding with this project after the manufacturing and initial testing of the first prototype is to integrate it with the Rescue boat. The current solution for propulsion on the boat is a Yamaha engine with a conventional water jet configuration. In this chapter the main focus is on determining changes that have to be made on the current Rescue boat for the new engine to fit and how integration between operator, engine, battery and other essential parts should be organised and dealt with.

9.1 Sections and Integration

The Rescue boat will be sectioned up into six parts, or modules, although future additions might be needed. Each part should be made so that it can be modified and changed for improvements or future upgrades without affecting surrounding modules. Hence, each part should have a defined interface and if possible a defined geometrical shape.

9.1.1 Rescue Boat

As described earlier the Rescue boat is a design by Fredrik Falkman and gives constraints on their subsequent parts. The boat has both a practical application as well as a structural to support all other parts of the system. Currently fitted on the boat is a Yamaha engine with a regular water jet propulsion. To fit the new Rim jet iteration to the hull will have to be made, both the fitting (interface) between the boat and the jet as well as the inlet duct will have to be adapted for the new engine. A thorough inspection of available space within the boat will have to be conducted to evaluate where each of the listed parts (modules) could be fitted for optimal performance and assembly.

9.1.2 Rim jet

The Rim Jet is connected physically to the inlet duct to transfer the propulsion force but also through power wires from the control box. The current connection or interface between the Rim jet and the boat are ten evenly spaced bolt going through the Bearing housing RS and in to the hull of the Rescue boat. The used interface between the engine and the control box are two power wires as well as a thinner power cable for the temperature sensor. All of these connect to the Control box with preexisting wires. To steer the vessel the Rim jet is also connected with a rod from the steering cable to the Steering Nozzle, as well as a ether mechanic or hydraulic actuation of the Reverse bucket. Within the Rim jet there is also two sub modules, the Rotor and Stator blades. As mentioned previously the chosen design of the blades makes them easy to change for service and maintenance as well as adapting to diffident tasks at hand.

9.1.3 Control box

To deliver the right amount of power to the engine a control box is necessary. The engine was provided with a control box by Marna and has three interfaces, one for the engine power, one for the power source and a third for the regulator (the pilot of the vessel). The location of the control box is important as it should be centrally placed between the engine, battery and driver for optimal performance and reduced latency.

9.1.4 Battery solution

As mentioned previously the battery solution for the Rescue boat is still not determined, as different options for the battery, depending on the space within the hull as well as weight distribution and power capacity, could be evaluated. However, the essential part of the battery are still more or less the same, it will have a output line as well as a charging line. For the charging it could be an option to have the converter of AC to DC externally to save space and weight as the vessel will be used exclusively in SSRS operations and therefore charged either at the operational headquarters or from a larger SSRS vessel. If the battery solution supports fast charging an issue that might occur is heat generated by the battery while charging. However, if the batteries are placed in contact with the bottom hull of the craft the cooling of surrounding water should solve this issue. This is of course under the preconception that the hull can withstand the heat generated and that forces against the hull does not damage the batteries.

9.1.5 Manoeuvring

For SSRS correct and efficient manoeuvring is essential for their operations. The connection between the driver and the craft is mainly done through the steering wheel, however controlling the craft could also be done remotely. A study by Gustav Lindberg, Hampus Bergh and John Skötte from Chalmers University of Technology investigate and implement a autonomous system that controls and follows a larger rescue vessel (World Maritime Affairs, 2020). Having said that, the system is still in development and will not be included in this module.

As of now the manoeuvring module, or section, symbolises the connection between the driver and the craft. Therefore the interface is the handlebars. However, the module can be broken down into sub-modules for each part of the craft that it controls. Depending on the solution for transmitting the information from the driver to the sub module; mechanical, hydraulic or digital, the corresponding interface will change. As of now the controls are as follows:

Table 9.1: Interface between sub module and handle bars

Sub module	**Interface**
Thrust	Digital
Steering left and right	Mechanical
Reverse	Mechanical

Important to consider is the transfer of module responsibility when and if the control system becomes completely digital. In that scenario the sub system of controls for the individual areas of the craft should be transferred to the control box unit as this is where the bulk of the control systems should be located. With a completely digital system new innovations and improvements regarding control and manoeuvring could be implemented. One such area is remote control as well as autonomous control. As previously mentioned, the work done by G. Lindberg, H. Bergh and J. Skötte proved an autonomous solutions was viable but future improvements was needed. With a digital system in place implementation of such a system wold only be a matter of updating the software. Another aspect is the control of the zero thrust function that makes the water craft turn on the spot. Currently, this can be achieved by manually controlling the trust while simultaneously putting the reverse bucket in a position that lets half of the water flow backward and half be moved forward by the reverse bucket. Controlling the vessel like this requires training and experience, and in extreme conditions could be one area of problem when dealing with multiple problems at once. With a digital system instead of a mechanical/hydraulic the zero thrust manoeuvring could be partly executed by the on board computer and could help the rescue personnel focus on their task at hand.

9.1.6 Integration

The Rescue boat acts as the platform that each other module fits on. Specific areas should be allocated for each module and they should all have a specified interface connecting them to either the boat or other modules. Depending on the digitisation of the rescue boat and other upgrades and improvements the interfaces might change in the future. However, to optimise the Rescue boat a modular design is key. With a modular design upgrades to certain parts can be made without altering other areas. It can also be used to adapt the vessel for different situations and tasks depending on the assignment at hand.

Table 9.2: Number of connections

Module	**Connections**
Rescue Boat	5
Rim jet	4
Control box	3
Battery solution	2
Handel bars	3

Chapter 10

Testing

Once manufacturing is complete testing of the prototype will commence. Depending on the situation and collaboration opportunities with other companies, such as previously mentioned Kongsberg, either water tunnel testing or more likely open water testing will be performed. Since the withdrawal of Kongsberg as testing facility preliminary testings will have to be executed by SSRS on open water. To do this a systematic approach is necessary to accurately test and validate the design.

10.1 Test on Rescue Boat

Without the expertise and equipment at Kongsberg SSRS will now have to test and evaluate the prototype with simpler methods. The following is a recommended solution to test the engine for the different requirements set by SSRS. As with all parts of this project cost and simplicity is prioritised and accuracy might be neglected for a simpler but more affordable solution. Until the use of a water tunnel can be explored the rim jet will have to be mounted to the Rescue boat for testing. Depending on the power solution for the engine it might be necessary to add ballast to the vessel to simulate the expected weight of the final vessel design. The following solutions for testing is based on the recommendations from ITTC "Recommended Procedures and Guidelines for Waterjet System Performance" from 2011(International Towing Tank Conference, 2011). According to their website “The International Towing Tank Conference is a voluntary association of worldwide organisations that have the responsibility for the prediction of the hydrodynamic performance of ships and marine installations based on the results of physical and numerical experiments.”

(International Towing Tank Conference, 2020). Amongst others, both SSPA and Kongsberg is part of the association.

10.1.1 Bollard Pull

According to ITTC, measuring water jet bollard pull (thrust at 0 knots) is categorised as optional. However, in the case for SSRS Bollard pull is one of the most important requirements. Therefore, correct setup and measuring tools must be used to retrieve optimal test data under current circumstances. ITTC recommends using a force transducer if the system is free floating. If the system is free floating it needs to be supported sideways and vertically in a way that does not affect the thrust measurement.

For testing of the Rim jet on the Rescue boat the system can be seen as free floating. If the tests are executed without a steering bucket it could be necessary to use a form of guide rails or fixating ropes so that the boat does not turn sideways. If a steering bucket is used it can be preformed without thees precautions. In that case the pilot of the craft will have to steer the vessel upright when preforming the tests.

10.1.2 Engine maximum rotational speed

Measuring the rotational speed should be executed above water with a digital laser tachometer. It is essential to keep the speed constant during the test. Removal of the stator housing might be necessary to collect data with the tachometer.

10.1.3 Maximum torque

One of the more difficult parts to test, especially without advanced equipment is the torque. The torque of the engine is specified by Marna. Nevertheless, when integrated in the design together with bearings and seals the torque will be different. ITTC suggests using a dynamometer on the shaft line to measure the torque. For a rim jet however, a problem arises when there is a lack of a shaft.

A solution to this is to manufacture a special rotor blade containing a shaft in the middle. Using this "test shaft" a dynamometer is connected and the system is then tested in this configuration. For initial testing of the Rim jet torque should be excluded for cost and equipment reasons and tested in a later stage.

10.1.4 Delivered power at maximum rotation per minute

The delivered power at maximum rpm is dependent on the both the duct losses as well as the blade design and imperfections within the engine. ITTC does not specify a method to measure this value as this is also effected by the boat hull and other aspects from external areas. A reasonably simple, although not so accurate solution would be:

1. Run the Rescue boat on open water at maximum power to determine the maximum speed. This will be discussed in the next section.

2. Drag the Rescue boat behind a larger ship at the same speed with a force transducer to determine the resistance between the water and the Rescue boat.

Knowing thees values the delivered power can be calculated as follows

$$P = Fv \tag{10.1}$$

Where P is Delivered power, F is the measured force when pulling the Rescue boat and v is the measured top speed.

10.1.5 Vessel Speed

Testing top speed on water can prove difficult as it is important to know in relation to what the max speed is measured. Depending on the currents in the water, the top speed relative to land might not be the same as top speed relative to the water. Therefore choosing the right body of water and weather condition is important to measure a valid cruise and top speed. Aspects to take into consideration:

1. Wind, as it will affect the aerodynamic properties of the Rescue boat and hence affect the speed.

2. Sea state, will move the Rescue boat vertically and affect both the speed and the speed readings.

3. Currents, could make the Rescue boat travel faster or slower relative to the observer if the measurements are taken from land.

4. The dimensions of the body of water chosen, is essential for measuring top speed is that the vessel. Making sure that there is enough space to do a continuous test without having to change direction is crucial to generate reliable data.

All thees parameters have to be taken into consideration when determining when, where and how to test both top speed as well as the other values previously mentioned.

10.1.6 Issues with proposed methods

All of the above presented testing solutions have issues regarding accuracy. Therefore, to generate a somewhat reliable test result multiple test runs have to be preformed on multiple occasions to extrapolate a average. ITTC presents recommendations for margin of error depending on the test preformed. However, these values are intended to be used for tests in a cavitation tunnel and not in open water. Because of this, margin of error will have to be determined for each test separately after evaluating the set up and surrounding factors.

To use as comparison the recommendations from ITTC is as follows

Table 10.1: ITTC recommended test accuracy

Test	**Recommended accuracy value**
Bollard pull (Thrust)	$\pm 2.0\%$
Maximum rotational speed	$\pm 0.05\%$
Maximum torque	$\pm 0.5\%$
Delivered power at maximum rpm	Not specified
Vessel speed	Not specified

Chapter 11

Discussion and Conclusions

11.1 Discussion DFMA

Implementing DFMA on the Rim Jet has had a positive effect on both part number, interface connections as well as expected cost. It has also improved the modularity of critical parts related to future improvements. The new design is now valid for production, due to the focus on simple shapes and a decreased number of operations on each part during manufacturing, as well as a simplified and faster assembly. It can be expected that these changes will benefit both initial production as well as future improvements and prototype iterations.

Due to the prototype nature of the Rim Jet project, the usage of DFMA could be seen as less linear when compared with more standardised examples such as the Flow Valve presented by Prakash et al, which experienced similar positive results from implementing DFMA. In particular, the DFMA analysis phase had to be altered for the Rim Jet-project. Hence, a different way of measuring and evaluating the changes is presented in this paper to quantify the improvements. Primarily, the goal was to generate a design that would be possible to produce within SKFs limits. The initial design had major design flaws that would prove unnecessarily complicated or even impossible to manufacture. With the use of DFMA, identification and correction of such areas could be addressed and improvements to the overall design were made. Even though a one unit project like the Rim Jet could be seen as problematic for the DFMA method, this project shows that most of the principles presented by Boothroyd are still applicable and do not require substantial work to be effective.

The work presented in this paper uses DFMA in a practical manner to improve and further progress the development of the Rim Jet. In contrast to the presented related research that often uses a conceptual product to evaluate the method theoretically. The final result could be argued to depict an authentic and practical way of implementing DFMA on a complex product.

It should be noted that, as discussed by Gerding et al., the success of DFMA could differ depending on what stage of development the project is at. It could be argued that the effects of DFMA could have been different for a similarly complex but more mature product and that implementing DFMA should always be evaluated from case to case. Arguments could be made for the method to be validated correctly, the lack of exact cost for each part as well as assembly time makes the results uncertain. However, it is obvious that substantial areas were improved without a "by the book" DFMA analysis including cost and assembly time. The most prominent area of improvement is the manufacturing feasibility. The Rim Jet design was developed and improved by two subsequent machine design students at KTH during the year of 2019. Nevertheless, the design remained unfeasible from a manufacturing standpoint. The current design is fully functional and feasible, it also consists of fewer parts as well as a reduced number of interfaces. It also follows a more logical assembly structure with six stages instead of eight and the total weight of the engine is substantially reduced.

During any type of product development, at some point, the project eventually move from the drawing board to a physical product. Whether it be a first prototype or an improved iteration of a current product going from raw material to finished product is no arbitrary procedure. A shape or form can be created through many different ways, starting with the shape of the raw material, to the tools at hand and requirement for the finished surfaces. Both Boothroyd and A. Read et al. discuss the issues related to a designer not knowing how the finished parts will be manufactured and tries to help engineers through hand books and software to improve in this area. It is apparent that this might be a part of a bigger issue. Both Muñoz as well as Santiago were highly educated machine engineers that spent numerous hours on the project. Even though, the resulting design was not realisable. Perhaps, if they would have been given the right tools and methods, this project might have been further along and time could have been spent on designing and iterating a more optimal design instead of still developing the first prototype.

An important aspect when implementing DFMA to a complex and novel design, instead of a mass manufactured product, is knowing how to apply the right tools and guidelines. Bothroyd presents the reader with an abundance of strategies and recommendations. Implementing everything could prove both exceedingly time consuming and perhaps even impossible for smaller projects. Instead, the importance lies in understanding the core of DFMA and extrapolating what is essential for this particular project. For the Rim Jet that could be the realisation that there might be a lack in tools and production possibilities and that the design has to be simple and easy to manufacture so that a first prototype can be built.

11.2 Discussion Rim Jet

Throughout this research the aim has been to further develop the Rim Jet solution for SSRS with a limited budget and resources. The improvements made to the design has resulted in less material, fewer manufacturing steps and a lower number of parts needed for producing the Rim Jet. The new design is lighter and easier to both manufacture and assemble. Many of the old issues regarding the complex shapes or the expensive manufacturing methods are solved and the modular qualities has been improved. With the flange solution to the rotor and stator blades, testing different types of blade configuration has been made simpler and in turn simplified future service and maintenance. One issue that has arisen with the new design is the reduction of the inlet diameter that affects the estimated requirements for head rise in the outlet stream. With the change from 195mm in diameter to 185mm the required inlet stream velocity has increased to meet the bollard pull requirements. However, as stated in the future work section of Andersen's paper, a more detailed analysis of the duct loss factor should be preformed and an increase in rotational speed could potentially produce the required bollard pull. No further calculations on the inlet duct factor has yet been performed. However, with a first prototype of the Rim Jet, testing of the inlet duct factor could be performed. Moreover, the engine is specified to have a nominal rotational speed of 4000 rpm. When Fredrik Falkman inspected the engine at Marna they tested the engine and speculated that it could potentially reach higher rpm without causing damage. With this in mind there are still a multitude of factors that are unknown both related to the Rim Jet as well as the complete Rescue boat. The hull calculations are made with the Savitsky's method which gives an approximate water to hull resistance and planing curve for a "standard" V-shape boat hull. The Rescue boat is not what many would say a "standard" hull and calculations could differ wildly from reality. Because of this complex situation a first prototype could answer many of the still unknown questions and parameters and shed light on what areas improvement is most needed.

Excluded in this research is a fluid dynamics analysis as well as FEM analysis of the current design to further optimise blade design and the weight to strength ratio. The primary target in the next phase of this project is to produce a first prototype to learn from the test results and iterate a second, improved, design. From the comparison to the work by Andresen it is evident that the smaller inlet diameter will result in higher demand for water speed within the engine. The configuration and shape of the Rotor and Stator blades have not been changed since Andresen's work other than the diameter change. This will most certainly affect the performance of the engine and require compensations from rotational speed and blade design to produce the correct thrust. With the modular design it is possible to easily change both the Rotor and Stator to try different versions. The simplicity to change configuration could also open up possibilities to benefit other research areas of RDT regarding Rotor/Stator interaction as presented in the work by Dubas, Bressloff and Sharkh (Dubas et al., 2015).

All parts except for the Rotor and Stator blades will be CNC machined. As presented in the work by Muñoz, parts could also be moulded and casted to reduce material needed and simplify production. However, for parts made from metal a casting process requires a mould which are expensive to make. Therefore, the casting option only becomes less expensive when multiple units are produced. For the Rim Jet prototype a CNC machining method is therefore preferred for its relatively low initial cost. In the case of parts made out of plastics or composites new leaps with in 3D printing could prove as adequate as moulding or even superior in cost and strength.

After the comparison of the new design to the design by Andersen it is evident that the changes made since the start of this project in 2014 will affect the performance of the Rim Jet and that there are still a wide array of areas that are uncertain. Using a modular design is key to easily modifying and improving the product on a tight budget. Initial key areas for modification is, as previously stated, the rotor and stator blades. It has been six years since Andersen designed the blades for this project and the parameters he used for his calculations have changed since then. Moving forward it will be important to focus on improving the blade design to optimise the jet stream. The work by Song, You-Jiang and Wen-Long concluded that a hub-less design would be more effective which contradicts Andersens results that the hub less solution reduces efficiency. Therefore, there are still areas of uncertainty regarding the theoretical estimations of the design and the simplest way for SSRS to answer this and other questions would be with a functioning prototype.

Integrating the engine with the Rescue boat is a critical part regarding performance and operational reliability. Sectioning the boat to modules eases future changes and modifications as well as making service and maintenance easier in future application at SSRS. The modules and sub modules presented in this work are second depending on their connections to other parts as well as their physical geometry. Depending on future developments within battery solutions and other areas related to water propulsion new modules or reorganisations might be necessary. One essential module reviewed in this paper is the battery which still is an issue for most completely electrical vessels. Initially a battery at about 200kg should be sufficient for testing. However, depending on the intended operational conditions for the Rescue boat future models could have a selection of different battery options depending on the required operational time. This could be beneficial depending on the task at hand as the weight of the craft highly affects both the drag and planning angle in the water, meaning that a lighter vessel could have better manoeuvrability as well as a higher top speed.

Finally, the testing solution proposed in this paper should be viewed as a method of proof of concept. All of the suggested procedures have an extensive margin of error and no exact results will be generated. However, the results will give an indication of weather the project is on the right path or if larger changes to certain areas have to be made to meet the requirements. Focus should be put on the bollard pull and the top speed of the vessel as these are of most importance for SSRS to determine future development of the Rim jet.

11.3 Conclusion

RDT is still an emerging solution for propulsion regarding small and medium size vessels. Related research on the subject encourages further investigation within the subject with a belief that RDT could be the future for efficient water propulsion. Continuing on the work made by previous students it was quickly identified that the design was not feasible for production or active use. A lack of production knowledge and material properties as well as assembly procedures and functionality had made the resulting design unsuitable for realisation as a first prototype.

In this paper a complete and production ready design is put forward though the use of DFMA. Decisions regarding geometrical shapes and manufacturing methods follow the recommendations and guidelines proposed by Boothroyd, with the aim to reduce the production cost as well as improve the overall modulariry of the Rim Jet. The new design is lighter, simpler and cheaper than the previous, whilst maintaining its intended functionality. This proves that for this single, complex and novel product the method of DFMA is a valid approach. However, as DFMA is primarily focused on optimising products made for serial production, some areas had to be neglected to ensure the viability.

Even though the DFMA analysis was not achievable exactly as presented by Boothroyd a comparison between the previous design and the current was possible and shows that improvements were made in all areas regarding production time, cost, part count, assembly time etc. It is uncertain how substantial some of these improvements are as there is a lack of comparative referential points connected to these areas of the Rim Jet design. However, it is evident that with the use of DFMA the design is now fully feasible and production ready. The total part count is reduced which in turn decreased the entire weight of the Rim Jet by 50kg. Proving that, even though a "by the book" analysis of the project was not possible, DFMA is still a valid tool for non-mass produced, novel and complex products.

11.4 Future work

After comparisons to Andersen's work it is evident that many factors are unknown and so far there is till no exact data to rely on. Therefore, a next step for the project is to manufacture a prototype to try and answer many of these questions. The production and subsequent integration of the Rim Jet with the Rescue boat will require modifications to the current vessel to incorporate the Rim Jet as well as decisions regarding power storage and operating controls. Using existing solutions on the market a battery with a weight of approximately 200kg should be sufficient for the Rim Jet. Utilising the modular design of the vessel, future upgrades on the battery module as well as other areas should be relatively simple and ease implementations of new, external, innovations.

The primary next step in this project is to manufacture and implement the Rim Jet on the Rescue boat. Moreover, certain areas should be prioritised to improve the design most effectively. The following list is ordered in priority determined from the work in this thesis starting with the most urgent. However, it is not necessary to follow them chronologically as circumstances can change and priorities could thus be altered.

- Produce a working prototype for proof of concept and initial testing. With basic testing methods presented in this paper an estimation of the Rim Jet capability's as well as comparisons to theoretical calculations can be made.

- With data from testing new modelling, simulations and optimisation of the blade design and configuration could significantly improve the performance of the Rim Jet. It would also further investigate Rotor-Stator interaction regarding hub less design and build on previous research related to this project.

- Optimise the weight to strength ratio, removing unnecessary material or shapes from the design to reduce the total weight whilst remaining the same, or improving, overall strength of the design using FEM and other simulation methods.
- Investigate modular integration of autonomous control as well as remote control of the vessel as a tool for SSRS during rescue missions.

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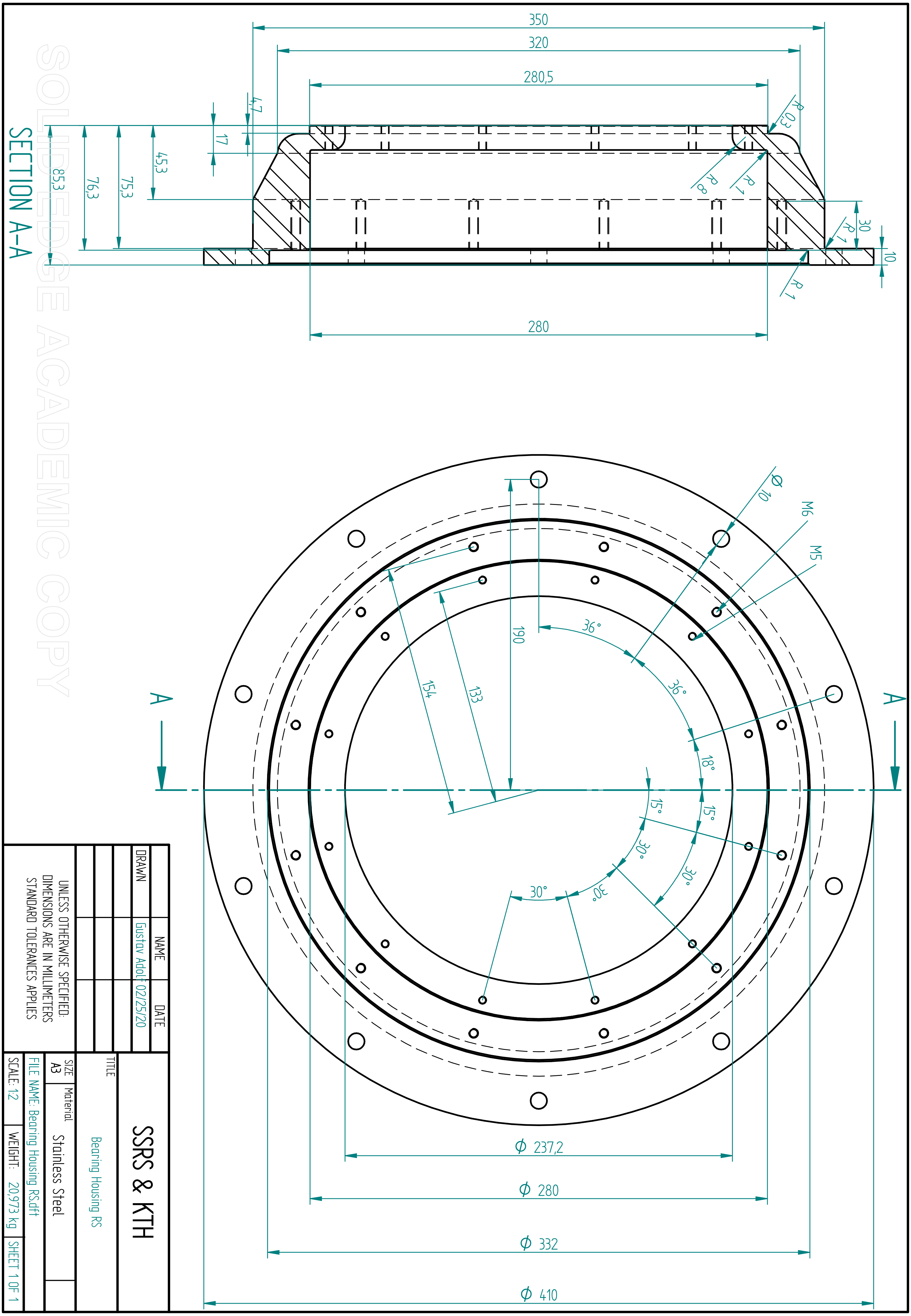
Appendix A

Drawings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R 1
R 1
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M5
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DIMENSIONS ARE IN MILLIMETERS
STANDARD TOLERANCES APPLIES
NAME
DATE
DRAWN
Gustav Adolf
02/25/20
SSRS & KTH
TITLE
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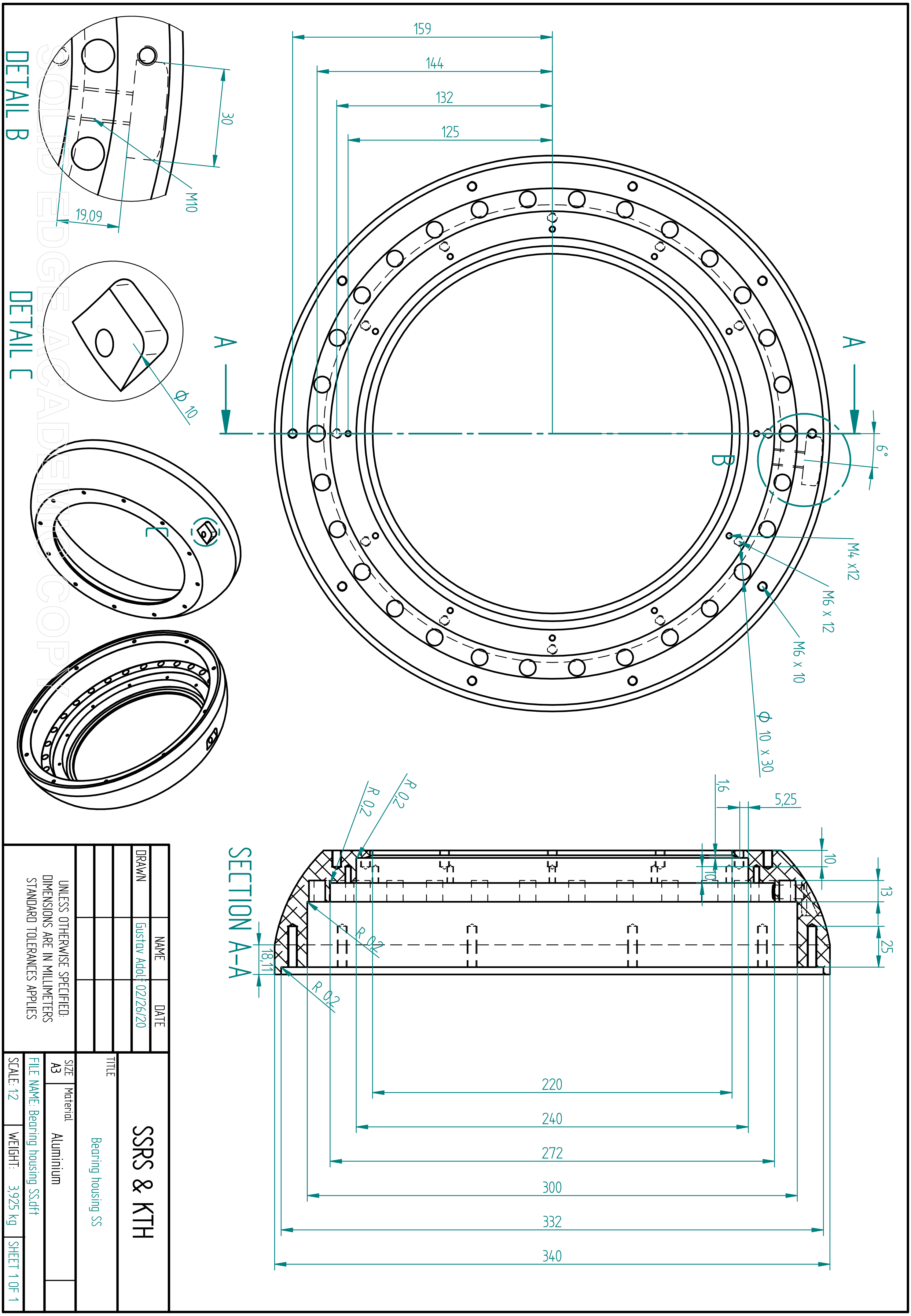
SHEET 1 OF 1



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NAME
DATE
DRAWN
Gustav Adolf
02/26/20
SSRS & KTH
TITLE
Bearing housing SS
SIZE
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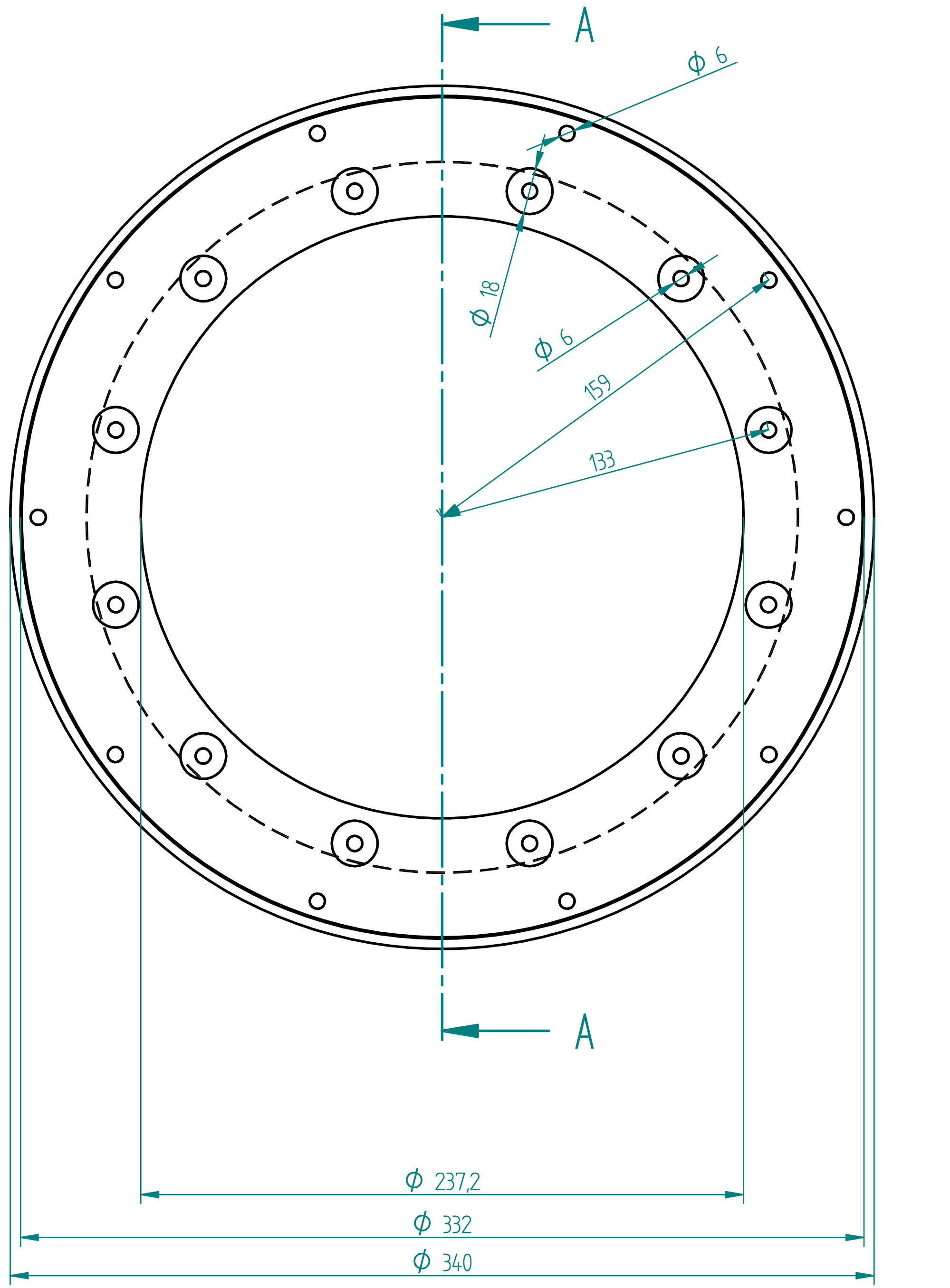

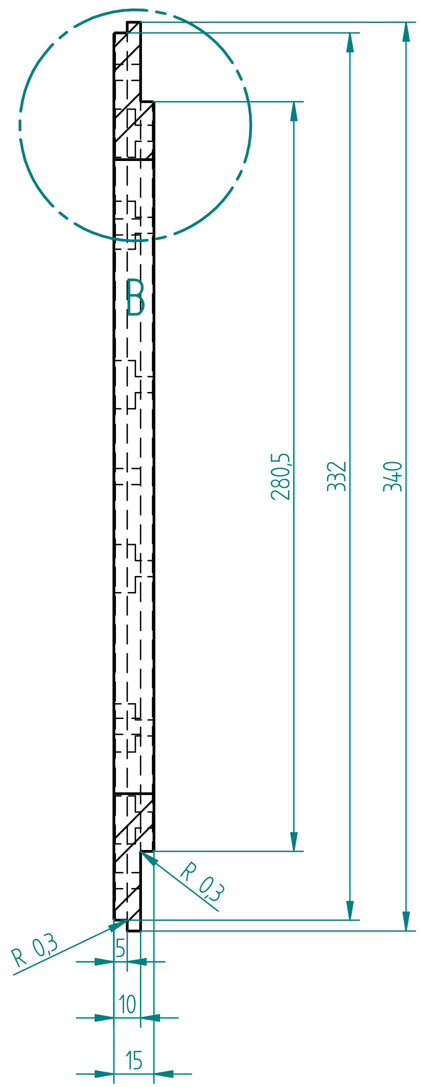

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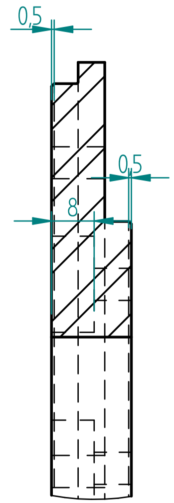

DETAIL B

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DRAWN	Gustav Adolf	03/03/20

SSRS & KTH

TITLE
Connector

SIZE	Material
A3	Stainless Steel

FILE NAME: Connector.dft

SCALE: 1:2	WEIGHT: 4,038 kg	SHEET 1 OF 1

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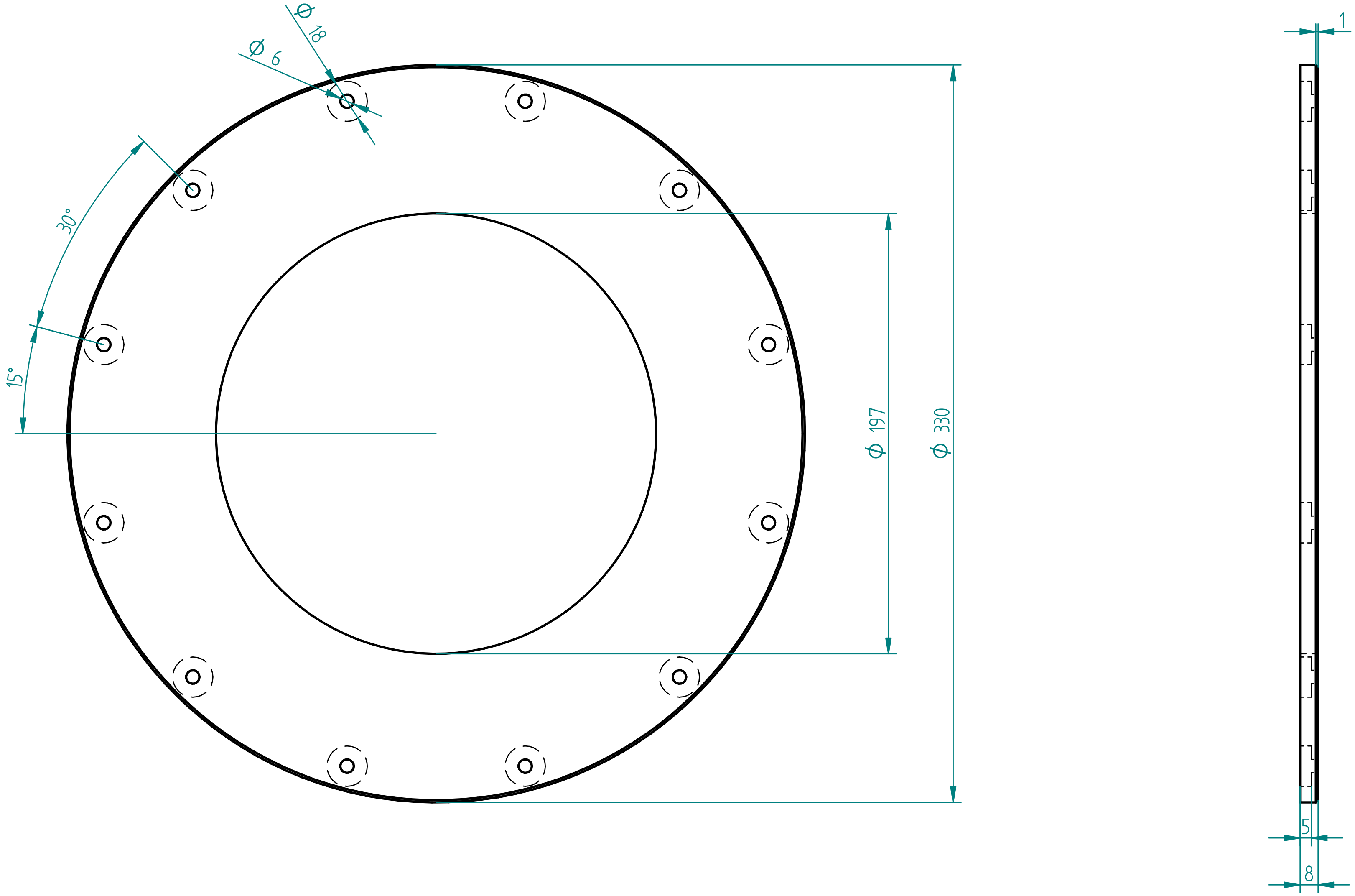


	NAME	DATE
DRAWN	Gustav Adolf	02/26/20

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
STANDARD TOLERANCES APPLIES

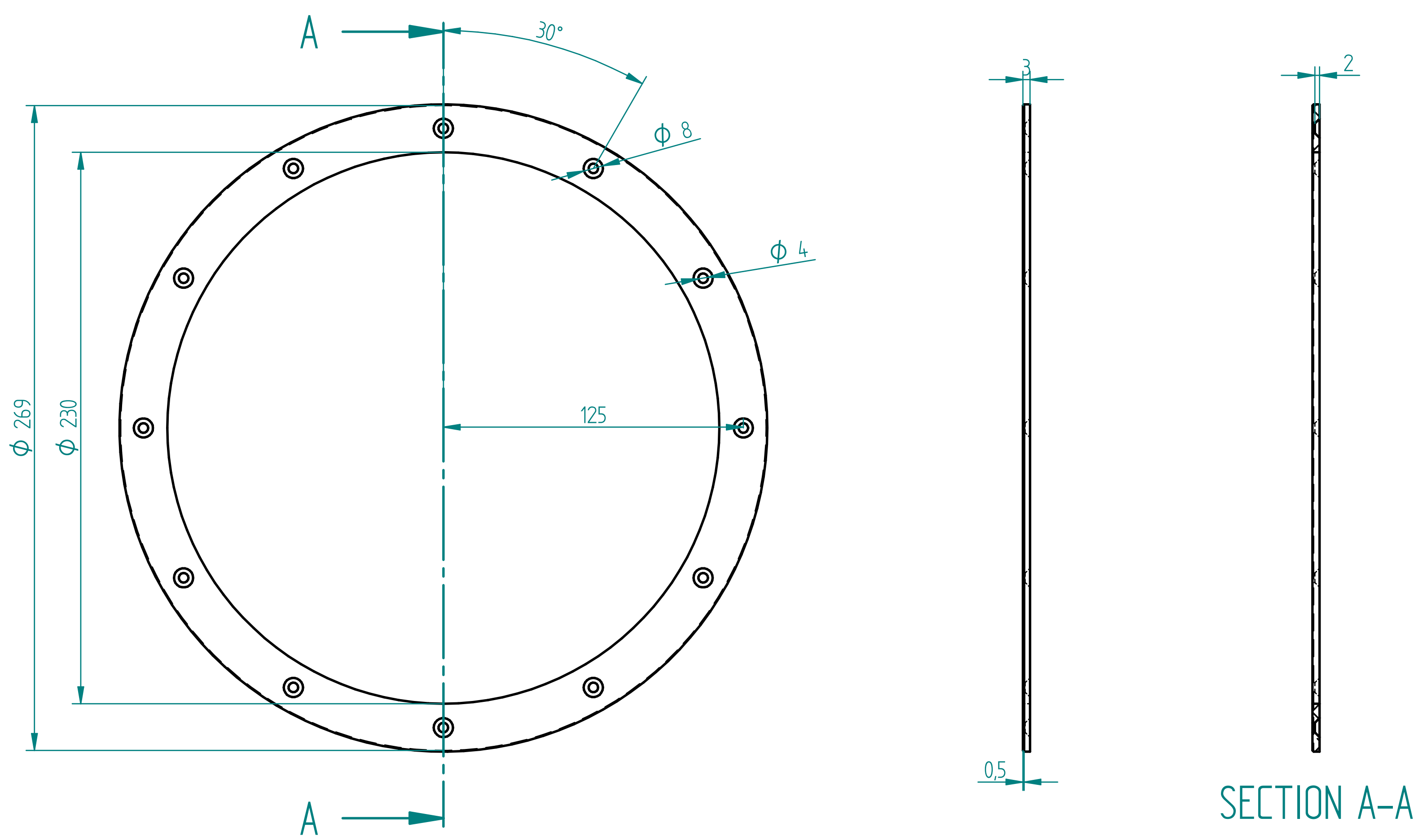
SSRS & KTH

TITLE
Cover Plate RS

SIZE A3 | Material Aluminium

FILE NAME: Cover Plate RS.dft

SCALE: 1:2 | WEIGHT: 1,149 kg | SHEET 1 OF 1



	NAME	DATE
DRAWN	Gustav Adolf	02/26/20

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
STANDARD TOLERANCES APPLIES

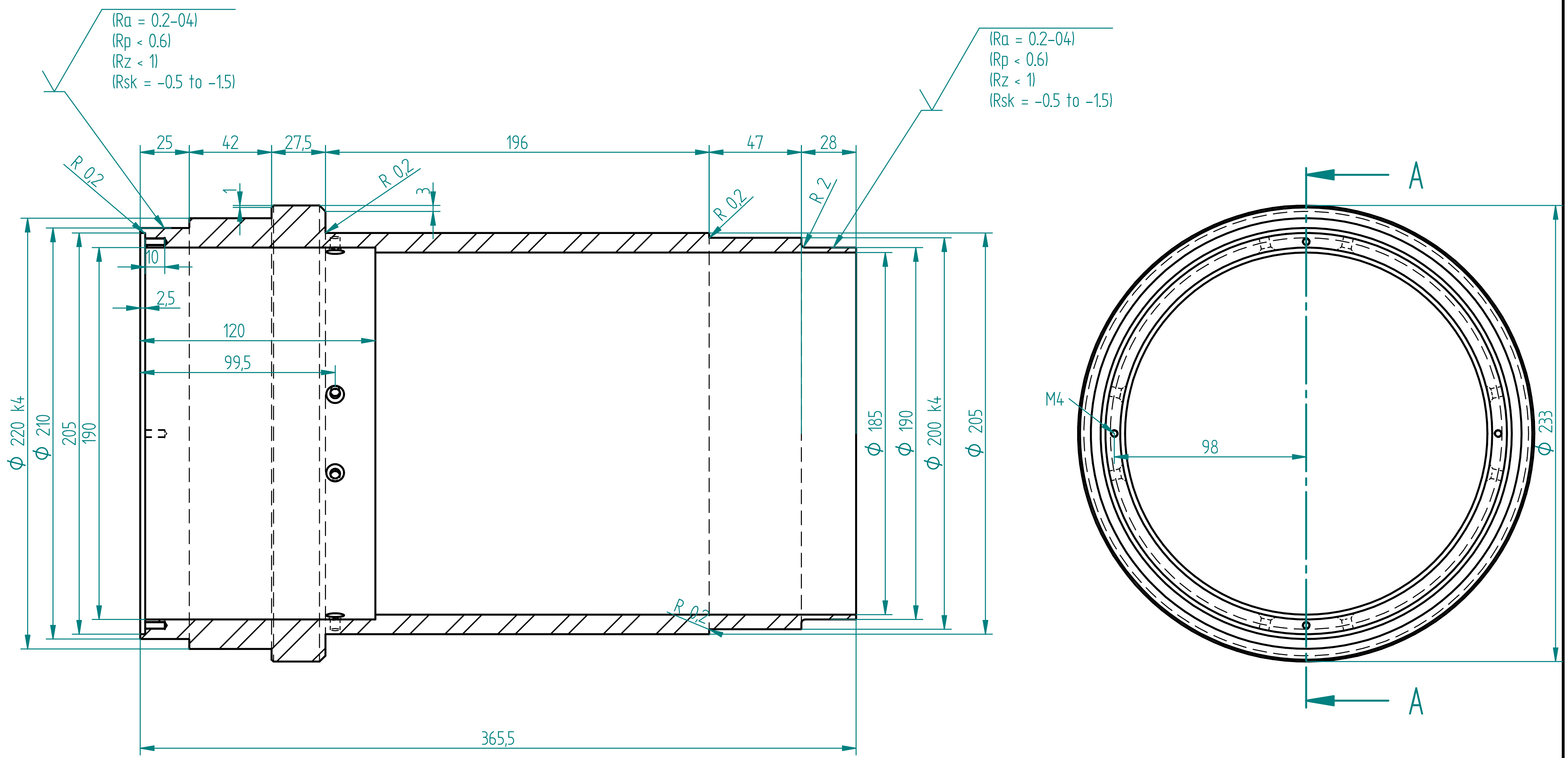
SSRS & KTH

TITLE
Cover Plate SS

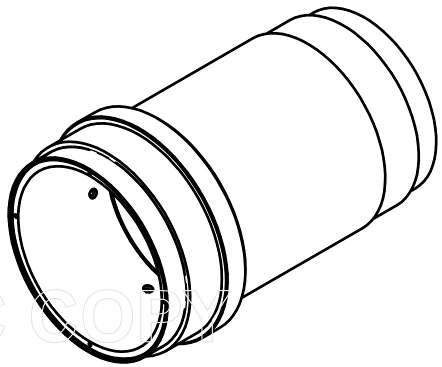
SIZE	Material
A3	Aluminium

FILE NAME: Cover Plate SS.dft

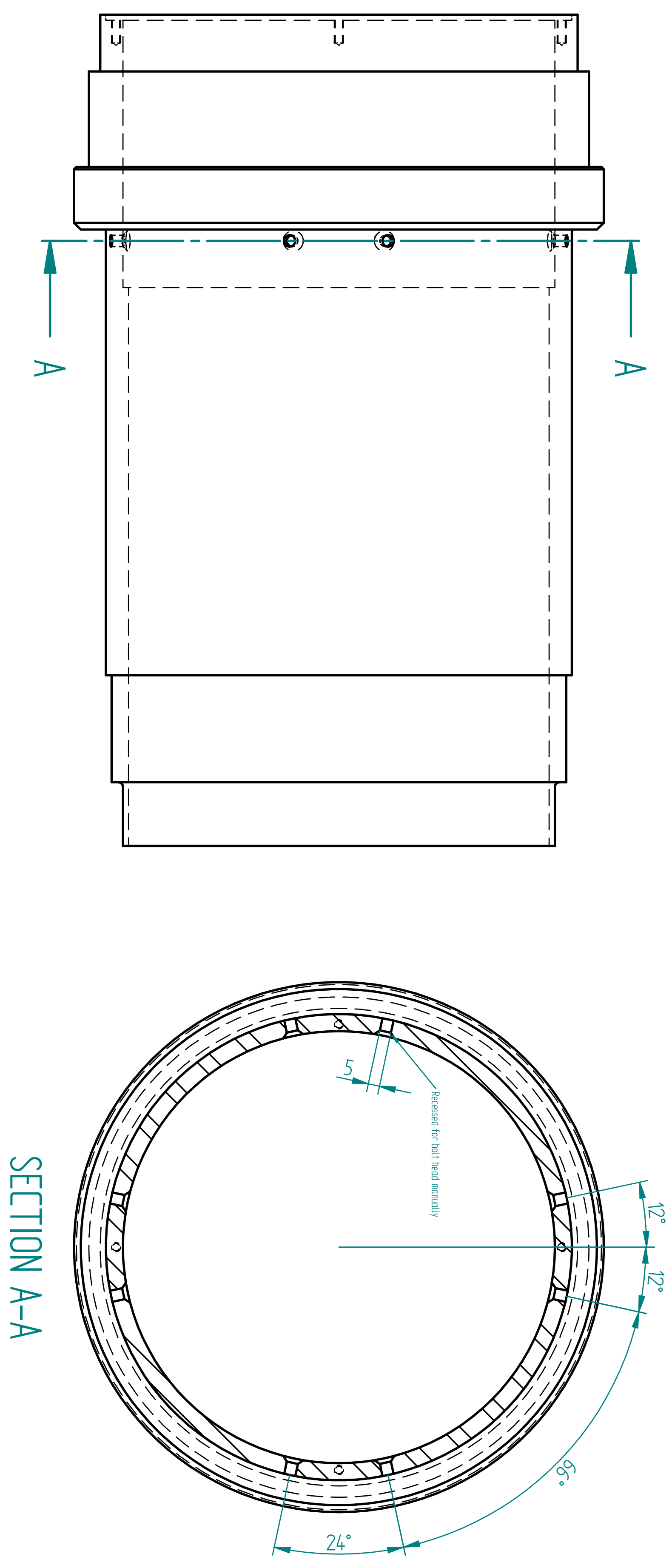
SCALE: 1:2	WEIGHT: 0,125 kg	SHEET 1 OF 1

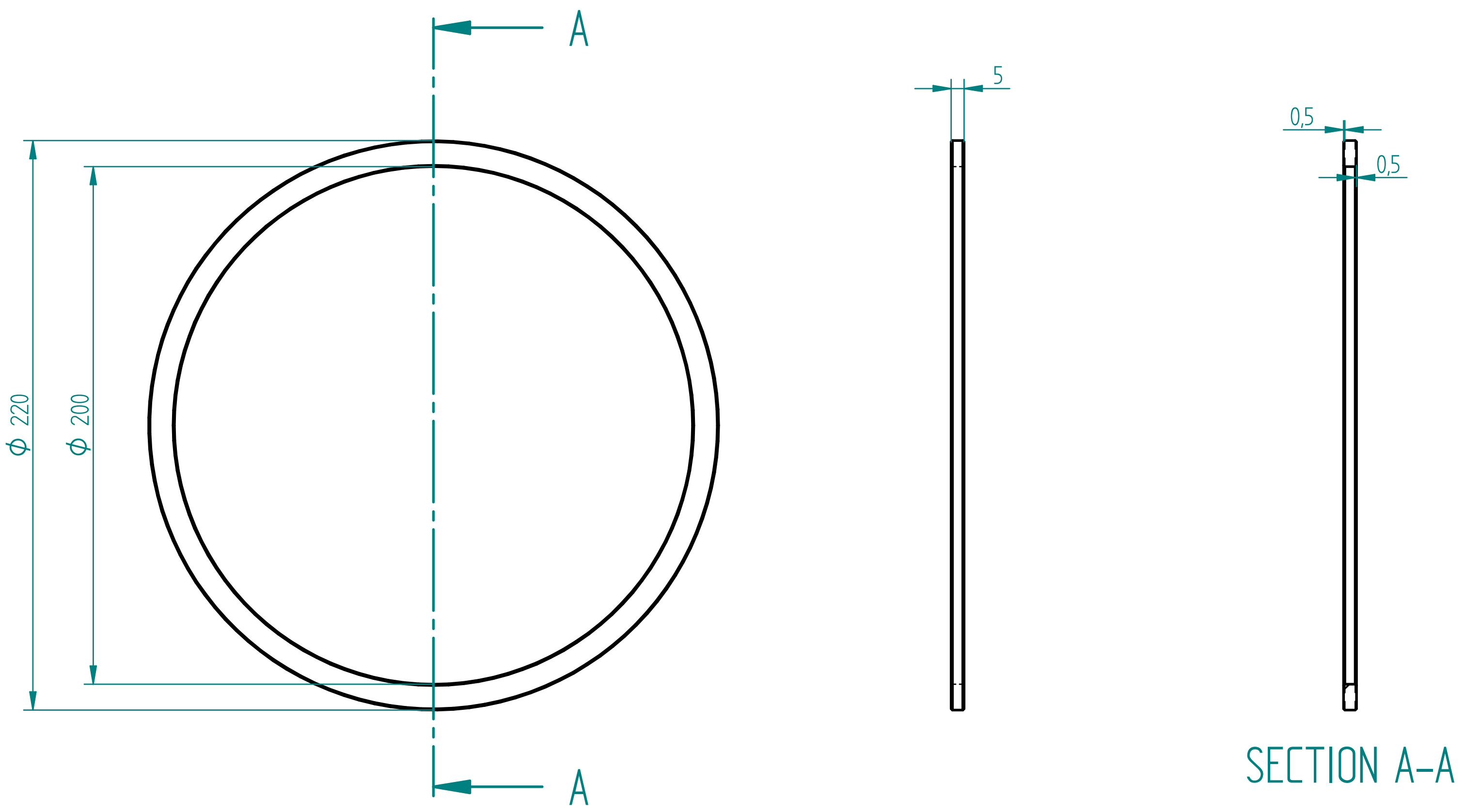


SECTION A-A



	NAME	DATE	SSRS & KTH
DRAWN	Gustav Adolf	02/26/20	TITLE Rotor Tube
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS STANDARD TOLERANCES APPLIES			SIZE A3 / Material Stainless Steel
			FILE NAME: Rotor Tube.dft
			SCALE: 1:2 / WEIGHT: 18,917 kg / SHEET 1 OF 2


A
A
SECTION A-A
5
Recessed for bolt head manually
12°
12°
66°
24°



	NAME	DATE
DRAWN	Gustav Adolf	02/26/20

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
STANDARD TOLERANCES APPLIES

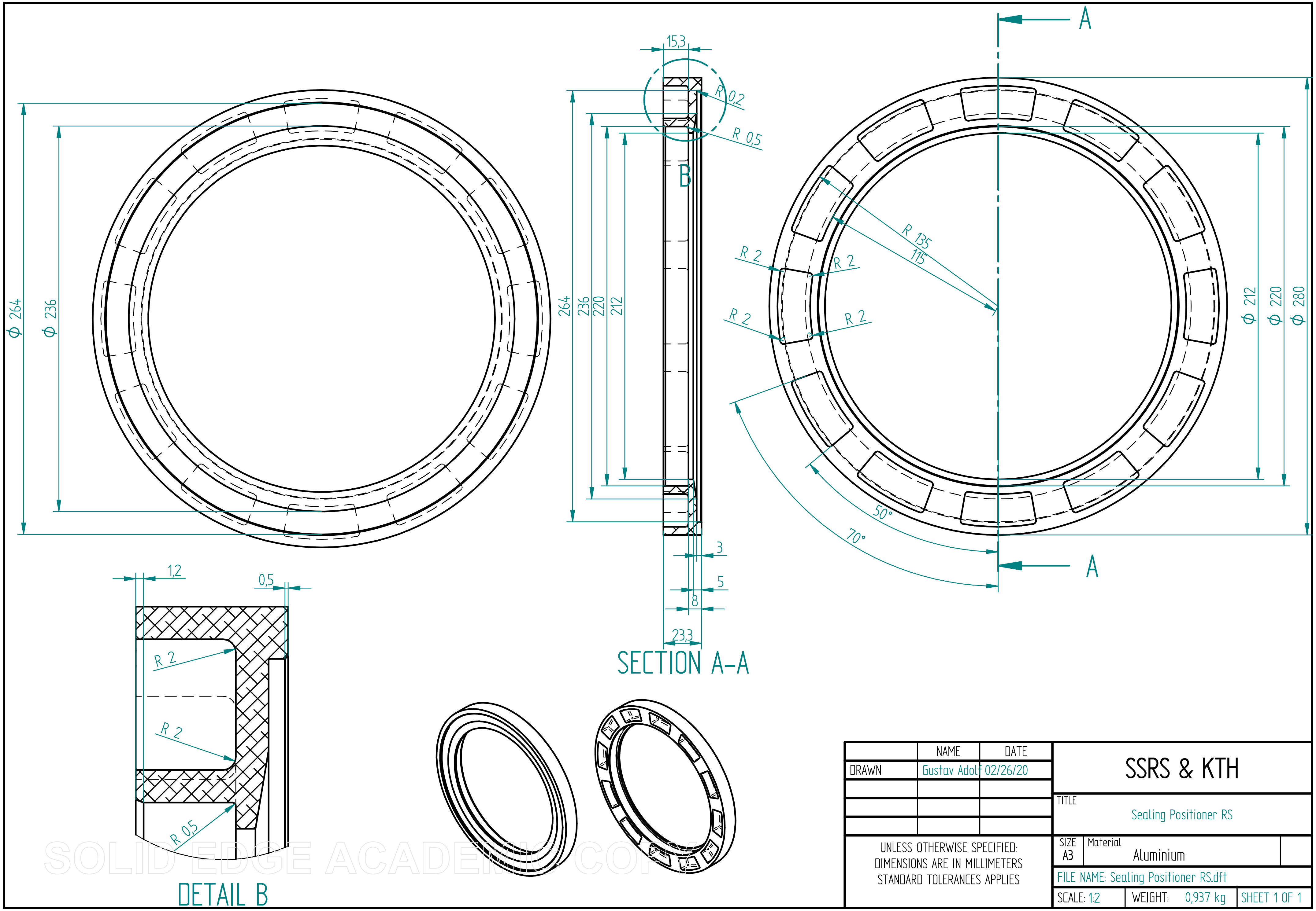
SSRS & KTH

TITLE
Rotor_extention

SIZE A3 | Material Stainless Steel

FILE NAME: Rotor_extention.dft

SCALE: 1:2 | WEIGHT: 0,256 kg | SHEET 1 OF 1



	NAME	DATE
DRAWN	Gustav Adolf	02/26/20

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
STANDARD TOLERANCES APPLIES

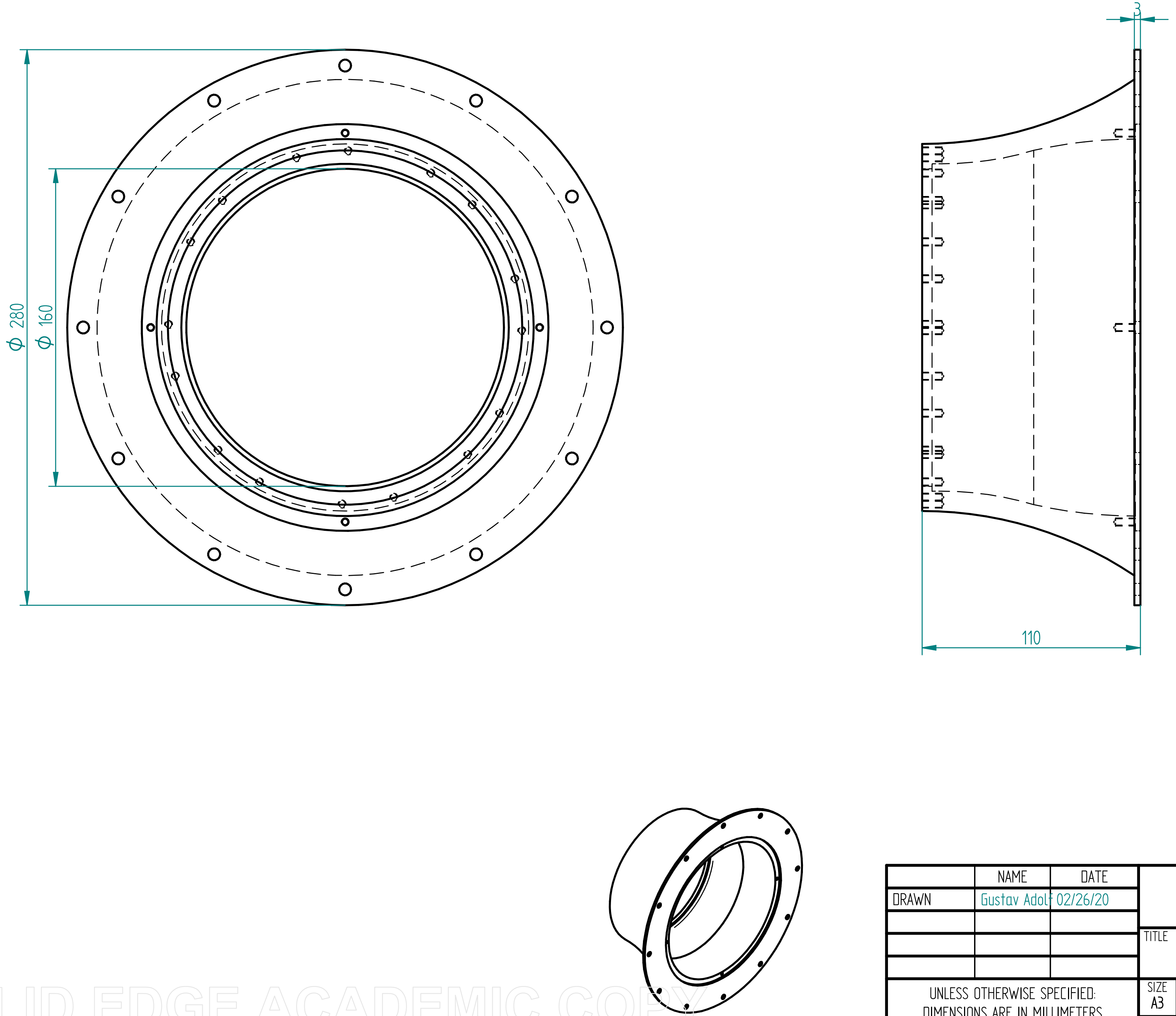
SSRS & KTH

TITLE
Sealing Positioner RS

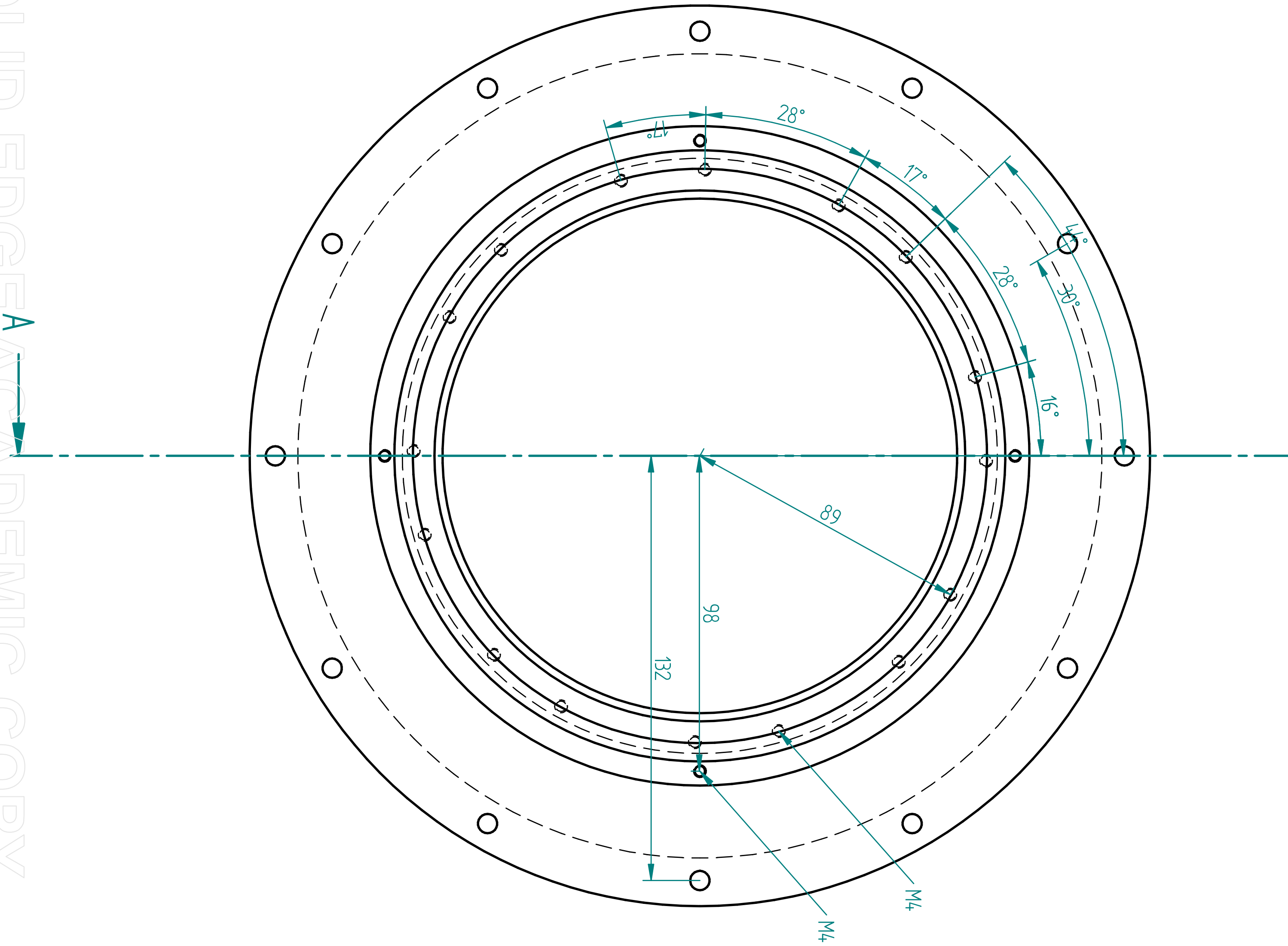
SIZE A3 | Material: Aluminium

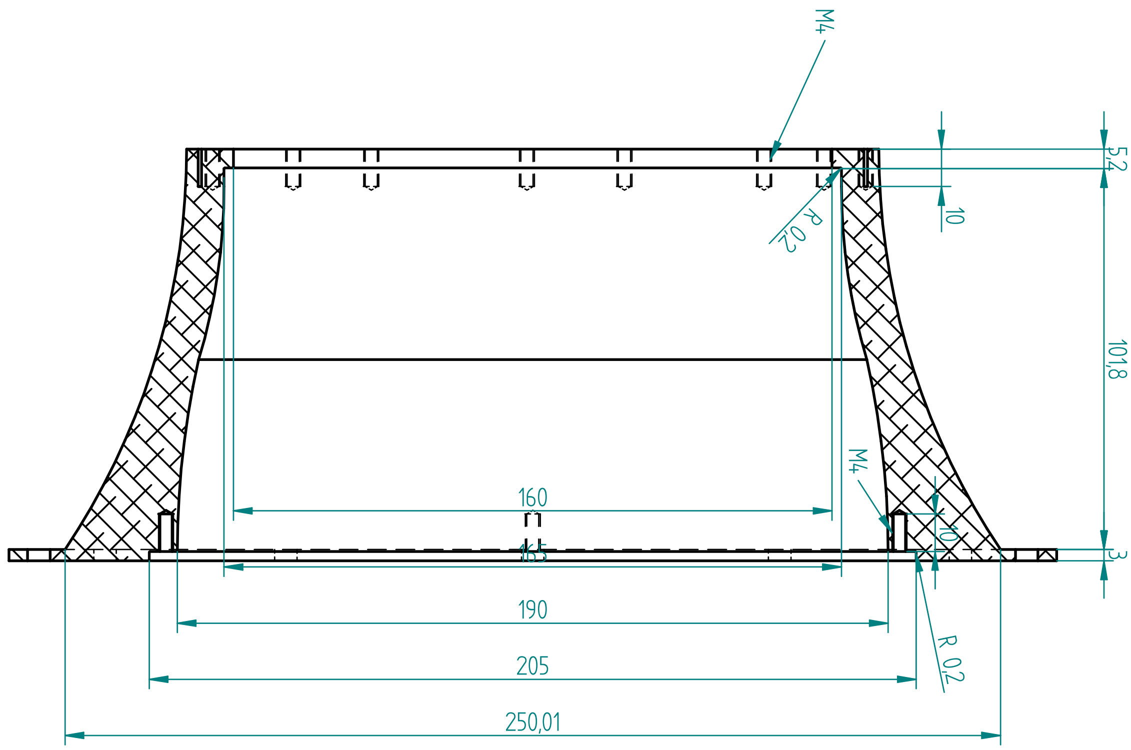
FILE NAME: Sealing Positioner RS.dft

SCALE: 1:2 | WEIGHT: 0,937 kg | SHEET 1 OF 1

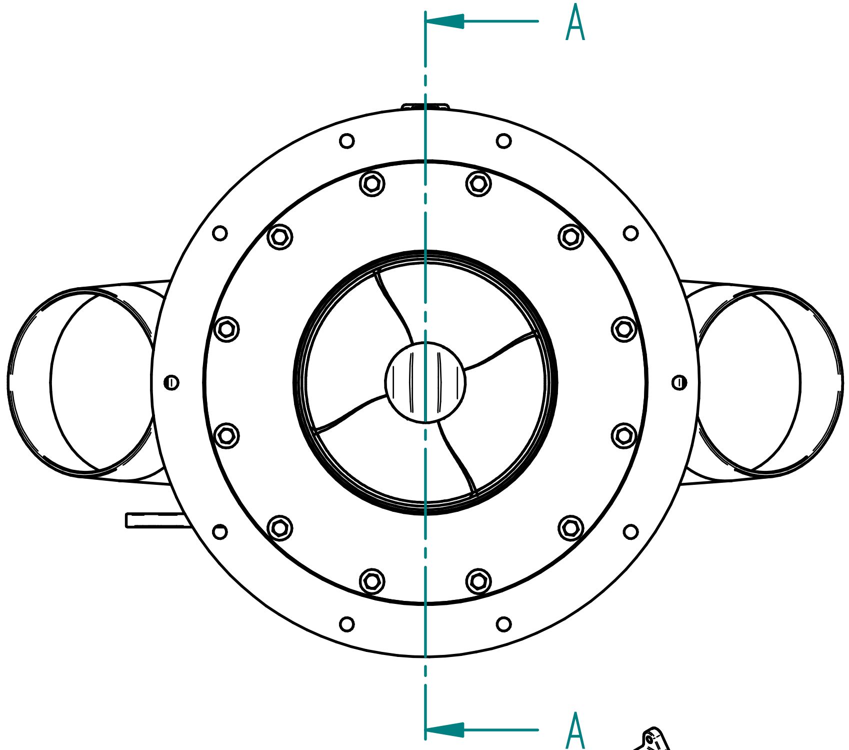


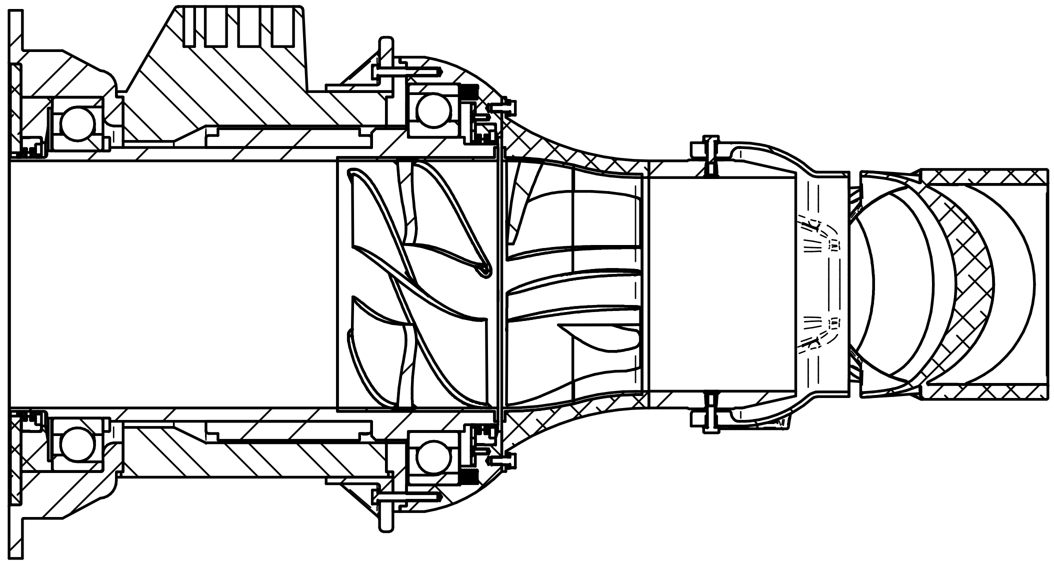
	NAME	DATE	SSRS & KTH
DRAWN	Gustav Adolf	02/26/20	TITLE: Stator blade housing
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS STANDARD TOLERANCES APPLIES			SIZE: A3 — Material: Aluminium
			FILE NAME: Stator blade housing.dft
			SCALE: 1:2 — WEIGHT: 2,834 kg — SHEET 1 OF 2


A
17°
28°
17°
41°
28°
30°
16°
89
98
132
M4
M4

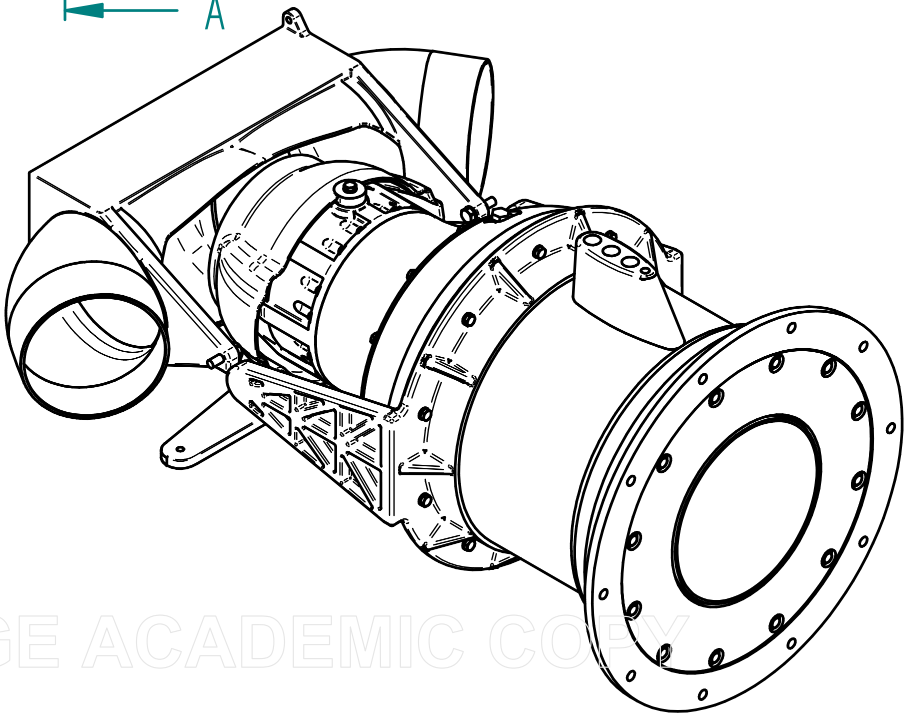

M4
5,2
10
R 0,2
101,8
M4
10
3
160
163
190
205
250,01
R 0,2

SECTION A–A

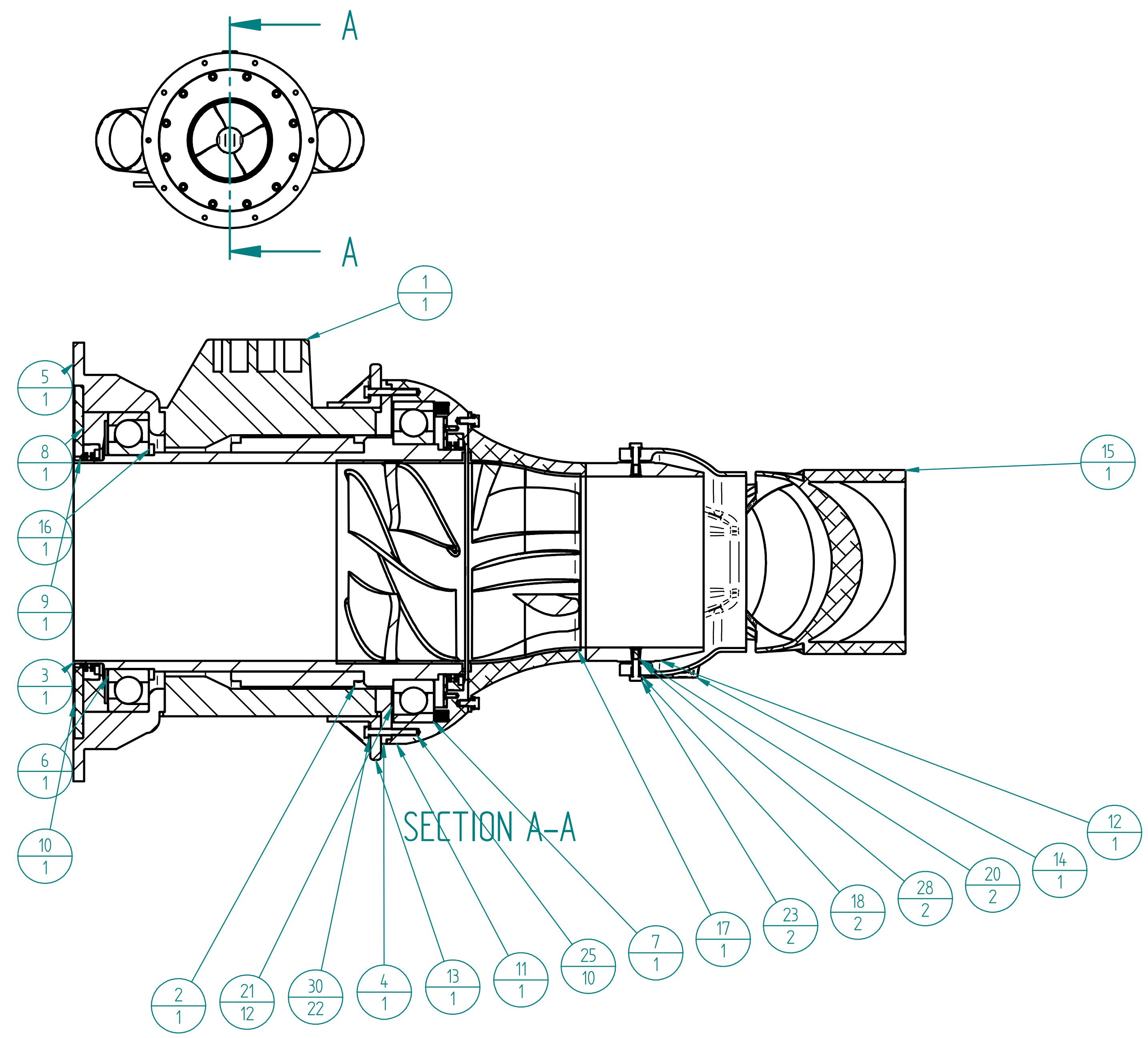




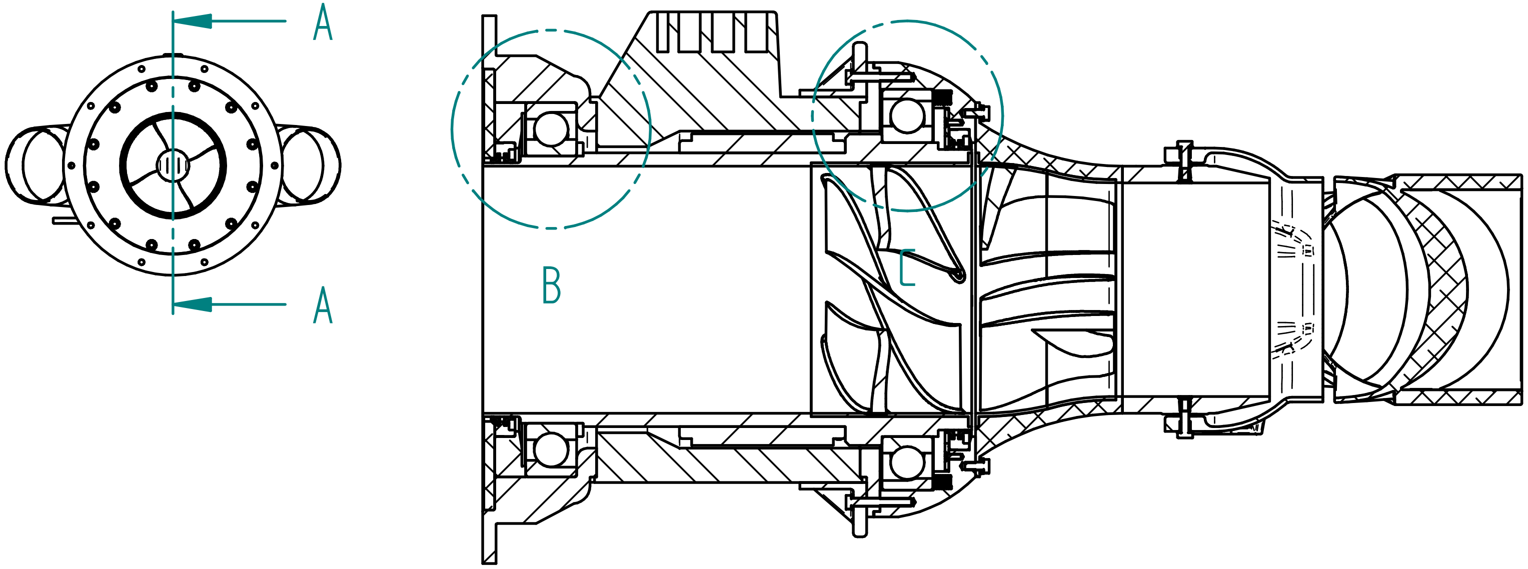
SECTION A-A



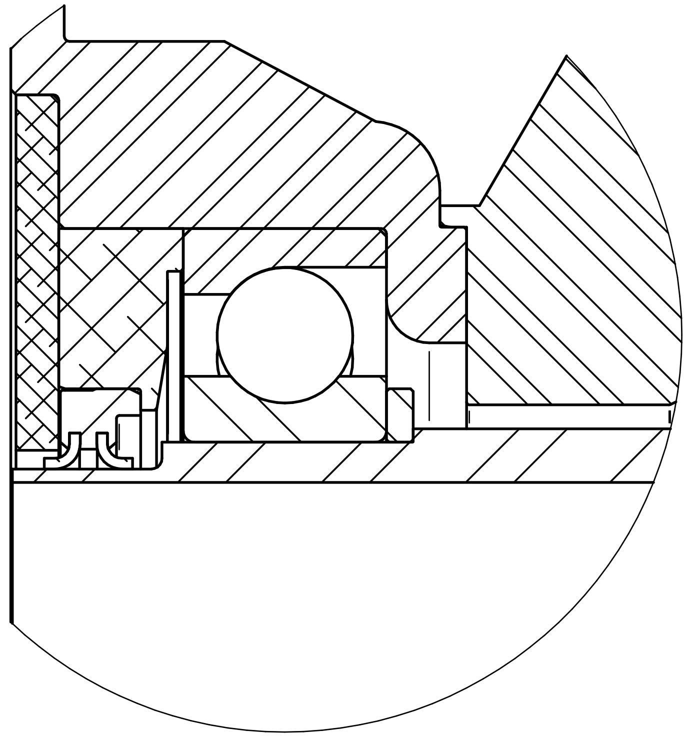
	NAME	DATE	SSRS & KTH
DRAWN	Gustav Adolf	02/26/20	TITLE: Rim-Jet (MAIN)
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS STANDARD TOLERANCES APPLIES			SIZE A3 — Material
			FILE NAME: Rim-Jet (MAIN).dft
			SCALE: 1:1 — WEIGHT: 132,636 kg — SHEET 1 OF 3



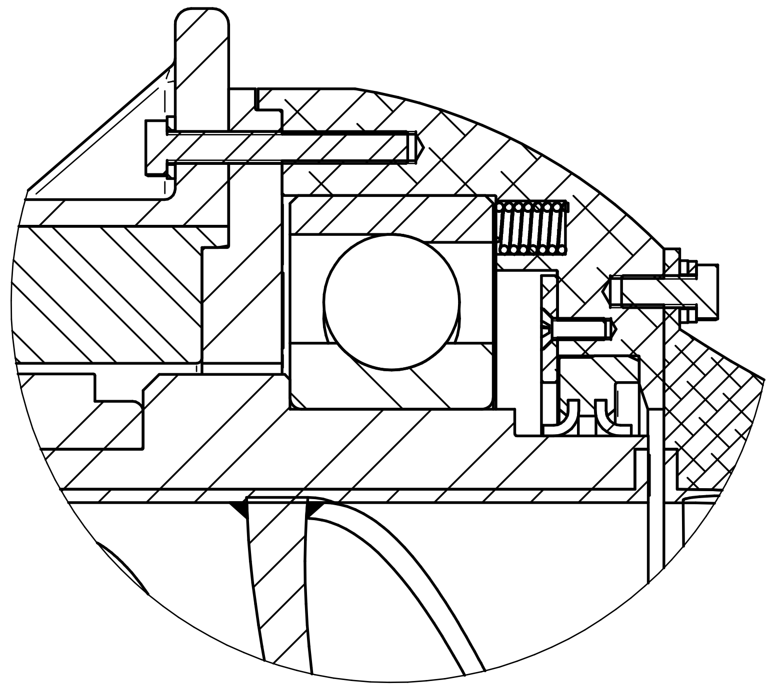
Item Number	File Name (no extension)	Author	Quantity
1	Motor Stator	Pablo	1
2	Motor Rotor	Pablo	1
3	Rotor Tube ASM	magnusmu	1
4	Connector	Pablo	1
5	Bearing Housing RS	Pablo	1
6	Bearing 71940 RS	psadmin	1
7	Bearing 71944 SS	psAdmin	1
8	Sealing Positioner RS	Pablo	1
9	Sealing TJD1B1900—T402M	Pablo	1
10	Cover Plate RS	Pablo	1
11	Bearing Housing SS &	magnusmu	1
12	Outlet Tube	Magnus	1
13	Reversing Bucket Support	Pablo	1
14	Steering Nozzle	Pablo	1
15	Reversing Bucket	Pablo	1
16	Rotor_extention	Gustav Adolf	1
17	Stator_blades	Gustav Adolf	1
18	Bushing PCMF 060808 E	psadmin	2
19*	Bushing PCMF 081009_5 E	psadmin	2
20	Insert M6	Pablo	2
21	Pass Through Bolts	Pablo	12
22*	Bolt M8 L30 DIN933	Magnus	2
23	Bolt M6 L25 DIN933	Pablo	2
24*	Bolt M4 L20 DIN933	Pablo	16
25	Bolt M6 L45 DIN933	Pablo	10
26*	Bolt M6 L30 DIN933	Pablo	12
27*	Washer M8 DIN125A	magnusmu	2
28	Washer M6 DIN9021	magnusmu	2
29*	Washer M4 DIN125	magnusmu	2
30	Washer M6 DIN125	magnusmu	22
31*	Grower M6	Pablo	12



SECTION A-A



DETAIL B



DETAIL C

TRITA TRITA-ITM-EX 2020:514