Nacelle Optimisation of Underwater Power Plant

Redesign of Pressure Compensator and Evaluation of Corrosion Resistance

Optimering av Generatorhus på ett Undervattenskraftverk
Omkonstruktion av en Tryckkompensator samt Utvärdering av Korrosionsmotstånd

Bachelor's thesis in the design engineer program

JENS ANDERSSON & OSCAR KLAMER

Institution of Product and Production Development
Product Development
CHALMERS UNIVERSITY OF TECHNOLOGY
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The project was conducted in cooperation with Minesto AB

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Cover:

[The final concept for the pressure compensator and corrosion prevention, explained in chapter *4.2 Pressure Compensating Concept* and chapter *4.3 Corrosion Prevention Concept*]
[Product and Production Development]

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Abstract

This report presents the result of a bachelor's thesis project conducted in cooperation with Minesto AB. Minesto develops an underwater power plant that generate electric energy from tidal currents. The project's aim was to develop some of this product's internal components to make it more compact and volume efficient. The result was a redesigned pressure compensator, a device that adjusts the internal pressure in submerged systems, since the original was considered to occupy too much space. Its function was preserved with minor modifications but its shape was changed so that it could fit in an unused area around a rotating shaft. The pressure compensator works with an oil filled system and generates an internal over pressurization of approximately 0.2 bar, preventing any ambient seawater from leaking into the system.

Furthermore the project aimed to evaluate the product's corrosion resistance and generate ideas for improvement. The nacelle, the outer housing containing the internal components, showed signs of stress corrosion cracking, a type of corrosion which only certain alloys under tensile stress are susceptible to, in its screw mounts. A suggested redesign of these screw mounts was presented. The suggested solution was to increase the number of mounts, increase their size and remove internal threads which are all factors that reduce the stress concentration. The report also includes a general guide of how to further evaluate the mounts corrosion resistance for future development.

Key words: Pressure Compensator, Corrosion Resistance, Power Plant, Stress Corrosion Cracking, Nacelle Optimisation, Corrosion, Fluid Filled Systems, Overpressurization.

Sammanfattning
Denna rapport presenterar resultatet av ett kandidatexamensarbete genomfört i samarbete med Minesto AB. Minesto utvecklar ett undervattenskraftverk som genererar elektrisk energi från tidvattenströmmar. Projektets syfte var att utveckla en del av kraftverkets interna komponenter för att göra det mer kompakt och volymeffektivt. Resultatet blev en nydesignad tryckkompensator, en komponent som justerar det inre trycket i dränkta system, eftersom den ursprungliga ansågs uppta för mycket volym. Tryckkompensatorns funktion bevarades med mindre modifieringar medan dess form förändrades för att kunna placeras i ett oanvänt område runt en roterande axel. Tryckkompensatorn arbetar med ett oljefyllt system och genererar ett internt övertryck på cirka 0,2 bar för att förhindra att omgivande havsvatten läcker in i systemet.

Vidare syftade projektet till att utvärdera kraftverkets korrosionsbeständighet och generera lösningsförslag till förbättringar. Generatorhuset, det yttre hölje som innehåller de interna komponenterna, visade tecken på spänningskorrosion i sina skruvfästen. Spänningskorrosion är en typ av korrosion som endast vissa metallegeringar under dragpåkänning är känsliga för. Ett lösningsförslag med omkonstruktion av dessa skruvfästen presenterades. Den föreslagna lösningen var att öka antalet fästen, öka deras storlek samt avlägsna inre gängor, vilka alla är faktorer som syftar till att minska spänningskoncentrationen i varje enskilt skruvfäste. Rapporten innehåller också allmän information kring hur korrosionsbeständigheten hos skruvfästena skall utvärderas inför framtida utveckling.

Nyckelord: Tryckkompensator, Korrosion, Korrosionsbeständighet, Undervattenskraftverk, Spänningskorrosion, Vätskefyllda system, Högt tryck.

Nomenclature

Symbols

p	= Pressure [100 000 Pa = 1 bar]
F	= Force [N]
A	= Area [m^2]
c	= Spring rate [N/m]
δ	= Spring deformation [mm]
D_t	= Wire thickness [mm]
D_m	= Mean spring diameter [mm]
L_0	= Unloaded spring length [mm]
L_n	= Minimum working length [mm]
n	= Number of springs

Dictionary

Crevice	= A small, narrow crack or space
Fairing	= A cap for reducing drag
Hydrolysis	= Chemical decomposition in which a compound is split into other compounds by reacting with water
Hysteresis	= The lag in response exhibited by an elastomer in reaction to change in the forces acting on it
Nacelle	= The enclosed part of a product in which the components are housed

Abbreviations

SCC	= Stress Corrosion Cracking

Table of Contents

1 Introduction

In this chapter the basic information regarding the project is described.

1.1 Background

Minesto develops a power plant concept driven by tidal currents below the sea surface. There is an existing 1:4 scale model that undergoes testing before a full-scale model will be developed. It is on this 1:4 model that Minesto is doing a degree project to further develop its nacelle. The project is presented in this report.

1.2 Project Aim

The project aims to further develop the existing nacelle designed by Minesto AB to make it more volume effective by redesigning the pressure compensator and modifying other components. It also aims to investigate previous cases of corrosion attacks, evaluate different methods to prevent it and suggest a design that could reduce the corrosion on the nacelle.

The prototypes that are created in this project will be conceptual and not ready for production. No physical models will be made and the result will be presented as 3D-models in Catia V5.

1.3 Criteria

The project is limited to the front part of whole cylindrical nacelle which includes generator, turbine shaft, bearings, seals and pressure compensator. The following criteria were requested by Minesto.

Components that shall be used:

- Generator Kollmorgen KBMS-43X04
- LEMO contacts
- 3-bladed turbine developed by Minesto

Physical requirements:

- Maximum outer housing diameter: 175 mm
- Axial force from turbine: 2 000 N
- Torque from turbine: 50 Nm
- Rotation speed of turbine: 1300 rpm

Further requirements:

- The pressure compensation shall be regulated by oil.
- The compensator shall hold an oil reservoir of minimum 60 ml
- The compensator shall establish an average overpressure of 0.2 bar inside the generator house compared to the ambient water pressure.
- The developed concept shall obtain a life span of 2 years of active use and be easy to service when needed.

1.4 Limitations

- No economic factors will be taken into account.
- The final concept do not have to be ready for production.
- The concepts developed will be adapted to the 1:4 scale model and not for the full scale product.
- The project only addresses the front part of the nacelle which includes the pressure compensator, the generator, bearings, sealings, the shaft and the turbine.

2 Theoretical Reference Frame

In the theoretical reference frame information and results from earlier studies are presented. All the subjects in this chapter are of relevance for the project and provide a greater understanding for the different factors that affect the project.

2.1 Minesto's Deep Green Concept

The deep green concept is a tidal power plant that generates electricity from tidal currents (Deep Green, 2015). Because of its ability to operate in low velocity currents it is applicable in areas where no other known technology can operate cost effectively. The product is described as a kite as seen in figure 1 and is supposed to operate in groups called arrays.

Figure 1 Minesto's 1:4 scale model in their Deep Green concept (Minesto, 2015).

The Deep Green kite is shown in figure 2 and consists of a wing (1) and a turbine located on the front which is by a shaft coupled to a generator in the nacelle (3) (Deep Green, 2015). A rudder (4) steers the kite's movement under the water in an 8-shaped trajectory. The struts (5) are connected to the tether (6) which is fastened to a foundation located on the seabed. The generated electricity is transferred through the tether which also accommodates communication cables and is connected to a larger system network in the array.

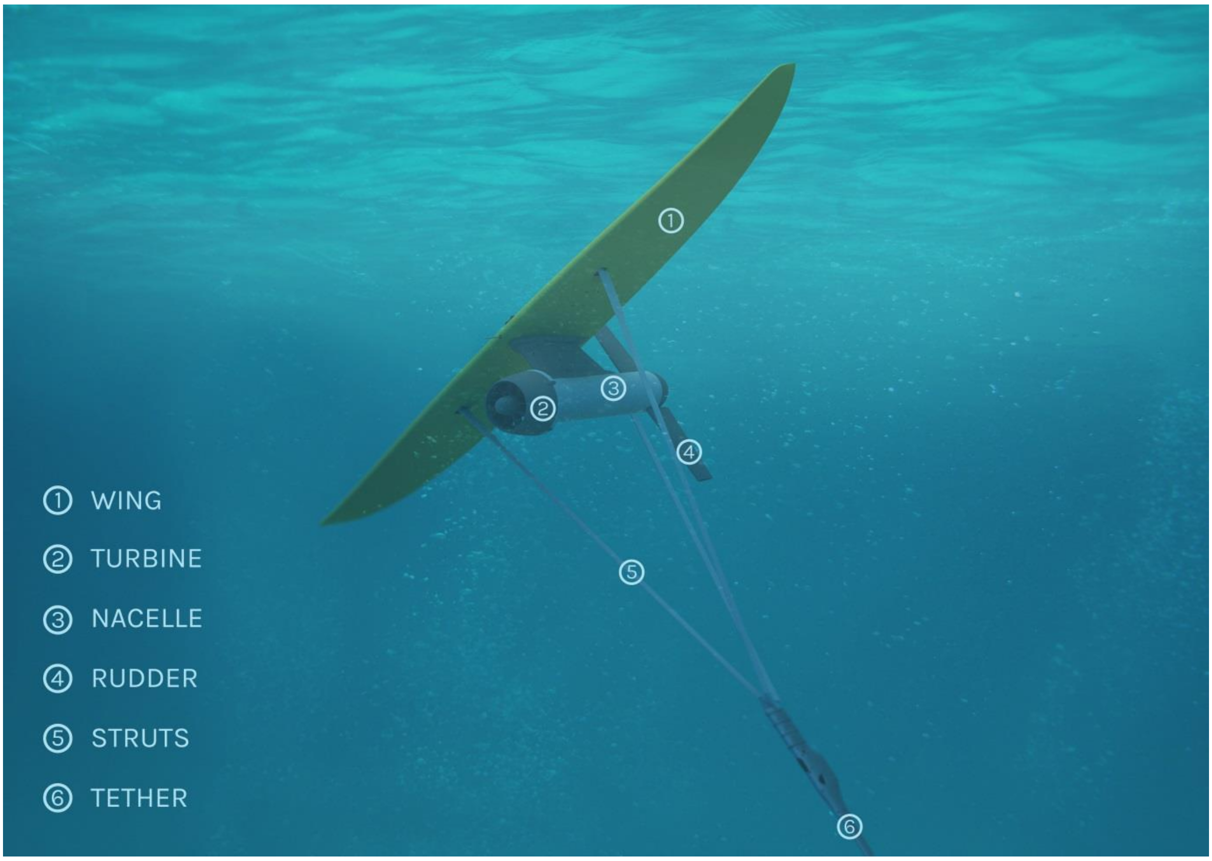

Figure 2 The Deep Green kite and its components (Minesto, 2015).

In figure 3 the kite's 8-pattern trajectory under water is shown. The kite can reach a speed 10 times higher than the water current (Deep Green, 2015).

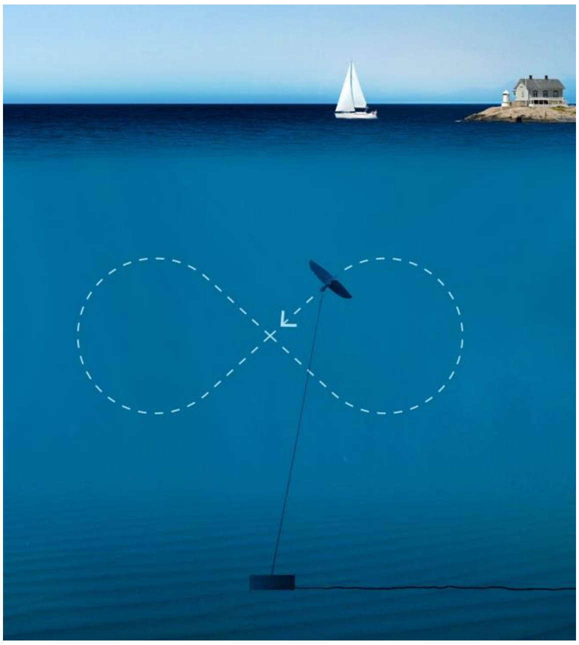

Figure 3 An illustration showing the 8 pattern that the kite moves along below the surface (Minesto, 2015).

2.2 Pressure Compensation

Components and systems that are used in deep sea operations will have to withstand a high hydrostatic pressure because of the depth. To avoid leakage and damages in the system there are two general methods when dealing with an excessive external pressure. Either the system is built very strong, often meaning thick and described as hard shell concepts, to simply keep the pressure out. Or the system is designed to compensate the internal pressure to match the external and therefore reduce the pressure differential (Hitchcox, 2012). The purpose of either design method is to protect internal components from an intrusion of the ambient environment, whether in air or submerged.

Below follows a review of fluid compensating systems. Hard shell and encapsulation concepts are described in appendix 1.

Fluid compensation

This technique is used in deep water operations by filling the system and letting internal components be submerged in a suitable fluid, using a pressure compensator in order to adjust the internal pressure to the ambient pressure (Mehnert, 1972, p. xi). The structural housing and seal requirements are therefore less demanding than for a hard shell concept since the fluid-to-sea-water pressure difference, Δp, can be reduced.

The fluid that the components are submerged in usually works as an electrical insulator, protecting the system from corrosion and lubricates machinery components (Mehnert, 1972, p. xiii). The heat transfer characteristics of the compensating fluid is often better than the characteristics of air which is an advantage when transferring the heat from internal components out to the cooling environment.

Another design aspect to take into consideration is how to enable and maintain a slightly higher pressure, a positive Δp, in the system compared to the ambient pressure. This would promote the internal fluid to leak out of the system rather than external fluids leaking in if a leakage would occur during operation (Mehnert, 1972, pp. I-2).

Mehnert (1972, p. xi) says "the most feasible design approach is not to fight depth pressure, but to design for and live with pressure" regarding how to deal with pressure in deep sea operations. He also states that this can be accomplished by using fluid-filling and pressure-compensating systems and components.

Several fluid compensation based concepts are described below.

Flexible bladder type

This design is usually made of an elastomeric membrane enclosed within a steel shell, as shown in figure 4. The bladder is then filled with the compensating fluid and exposed to the ambient pressure via a valve (Mehnert, 1972, pp. II-1). Figure 5 shows a more schematic illustration of this type of modified bladder accumulator where the gas valve connector is designed to be open to the surrounding water instead of being connected to a hydraulic system.

Figure 4 An accumulator modified to work as a pressure compensator (Globalspec, 2015).

As the flexible bladder is exposed to the ambient environment the ambient pressure will be transferred to the fluid. One way of creating a small but positive Δp between the internal and external pressure is through placing the bladder at a lower level than the rest of the system (Mehnert, 1972, pp. II-19). The bladder will then be exposed to a pressure slightly higher than the other components because of the depth difference.

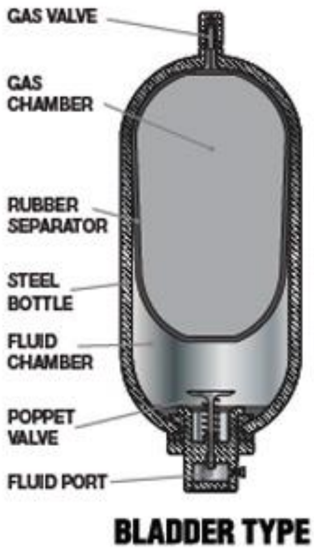

Figure 5 A schematic view of a modified accumulator (Tobul, 2015).

Bellows or convoluted tube

Bellows or convoluted tubes can be used as a reservoir. The bellows retract or expand during a pending pressure. Because of how the bellows are configured the retracting and expanding motion are very linear and controlled. This design can be constructed by either a metal or an elastomer but the elastomer bellows or tubes are more commonly used (Mehnert, 1972, pp. II-2). Using metal may also cause corrosion issues because of the ocean environment.

A spring which applies a load on the bellows can be used to create an overpressure in the internal system, as seen in figure 6.

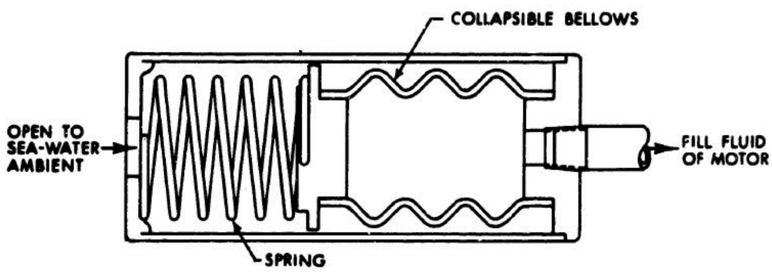

Figure 6 A schematic view of a pressure compensator using bellows (Mehnert, 1972).

Diaphragms
There are generally three types of diaphragms that are used; flat, convoluted and rolling diaphragms. All three are made of either solid or fabric-reinforced elastomeric material. For flat diaphragms the deflection or stroke is directly related to the exposed surface area and the elastomer stretch (Mehnert, 1972, pp. II-6). A flat diaphragm of a small surface area can develop positive or negative pressure differentials for a slight change in the fluid volume. While a convoluted diaphragm of similar size will provide an increased stroke without the constraint of elastomer stretch. Both types are illustrated in figure 7.

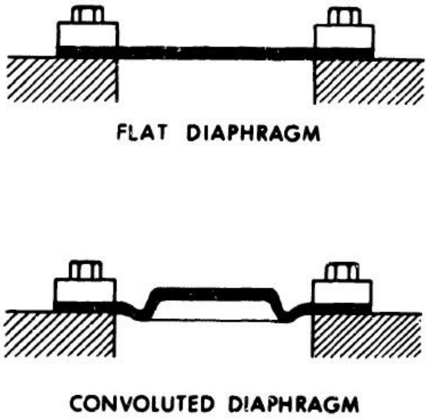

Figure 7 A schematic view of a flat diaphragm and a convoluted diaphragm (Mehnert, 1972).

A rolling diaphragm is basically a very slack diaphragm, a “top hat”, contained within a cylinder case and capable of a piston-type movement, see figure 8. The elastomer is usually reinforced with glass-fibre, PTFE, or with high tenacity rayon (Brown, 1995, pp. 370-371). The reinforcement helps to permit free circumferential elongation of the diaphragm with no axial elongation and gives a so called “true rolling” action. A plain elastomeric would not “roll true” and would also develop friction. The diaphragm keeps an intimate contact with the piston and its movement causes the diaphragm to roll up and down the axial clearance space, limited by the amount of slack available. Depending on the depth of the diaphragm this type can have a very large travel. The motion is usually smooth, continuous, free of friction and any hysteresis effects, since the diaphragm is not stretched because of the rolling motion.

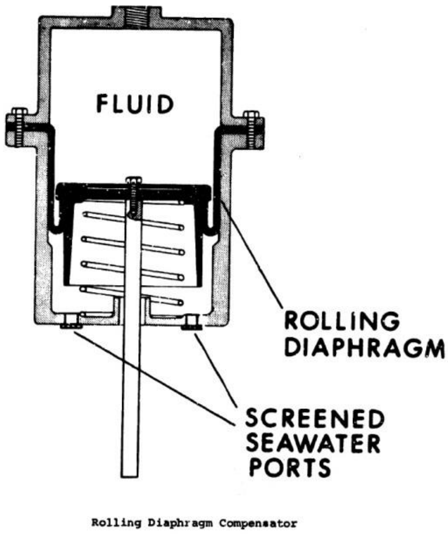

Figure 8 A schematic view of a rolling diaphragm (Mehnert, 1972).

Rolling diaphragms are often used in separated and external compensators. A spring can be used to create an over pressure if needed. The membranes abrasion and thinness could be a problem for applications that will be submerged for a longer amount of time (Mehnert, 1972, pp. II-6).

Design aspects to facilitate maintenance
When a fluid filled system is refilled with new oil between periods of submergence, one aspect that is important for the filling or draining process is where the vent ports are placed. Having two ports rather than one is an improvement. Placing these ports separately at the highest and lowest points of the system will further facilitate the process and reduce the amount of air in the system.

2.3 Corrosion

Corrosion is when a material, usually a metal, is being dissolved as a result of a chemical or an electrochemical reaction with its environment which gradually deteriorates its useful properties such as strength and appearance (Davis, 2014, pp. 1-2). In the term environment there are three important factors to take into consideration:

- Physical state - gas, liquid or solid.
- Chemical composition - concentration and what it consists of.
- Temperature.

For the corrosion process to initiate the material needs to be exposed to an electrolyte, a conductive solution such as saltwater, and the electrons must be able to travel between the anode and cathode surfaces (Javadi & Akhlaghirad, 1994).

Corrosion types

There are several types of corrosion and as they are initiated by different factors, both environmental and material, it can be difficult to identify which corrosion type the application is suffering from. However, each type corrodes the material differently which often can be visually identified and be a helpful indicator when trying to identify and prevent corrosion. Figure 9 displays several types of corrosion and below follows a few descriptions of corrosion types relevant for this project. For a further description of all corrosion types, see appendix 5.

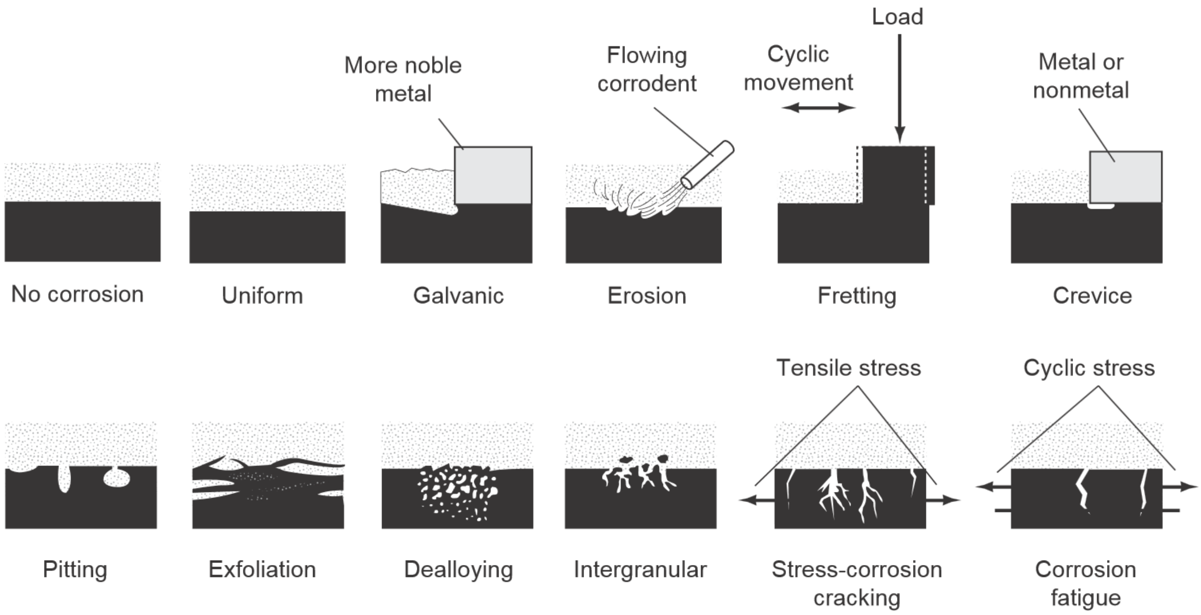

Figure 9 Illustration of different corrosion types and their effects (Davis, 2014)

Uniform corrosion

This is the most common type of corrosion and represents the biggest destruction of metal in general. As can be seen in figure 10 and 11 it spreads out evenly over the surface with a uniform corrosion rate (Mattsson, Korrosion, 2015).

Figure 10 Example of uniform corrosion (Tomson, 2015).

Figure 11 Schematic illustration of uniform corrosion (Davis, 2014).

Crevice corrosion

This type occurs at specific locations and is often associated with empty spaces, gaskets or bolts where crevices exists in acidic conditions or where depletion of oxygen can occur, see figure 12 and 13 (Mattsson, Spaltkorrosion, 2015).

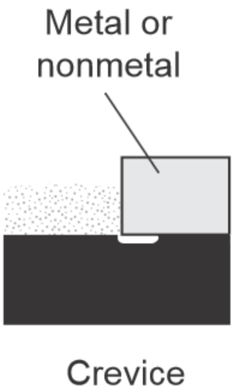

Figure 12 Schematic illustration of crevice corrosion (Davis, 2014).

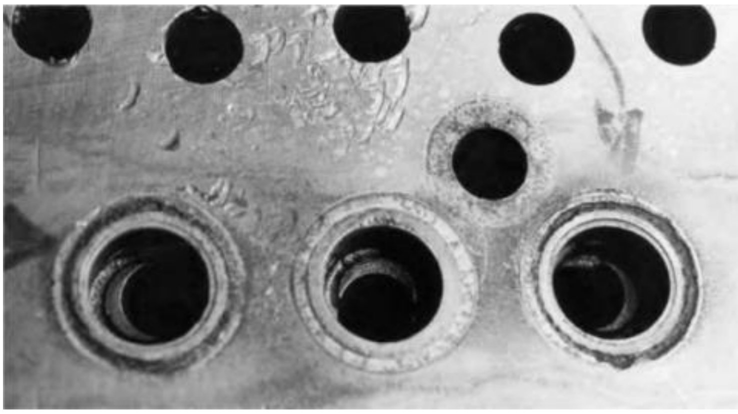

Figure 13 Example of crevice corrosion (Davis, 2014).

This can also occur as an effect of difficult fluid flows where the fluid pierces through to narrow spaces, or it gets there by condensation, and remains there over time and eventually causes corrosion. This is mostly a consequence of insufficient design (Davis, 2014, pp. 107-114). Passive metals, which are metals that create a protective oxide coating by nature, such as stainless steel and aluminium, are especially weak against this type of corrosion. This is rather unique since they otherwise are very corrosion resistant. The reason is that their oxide coating needs oxygen to remain strong and in these crevices it occur a depletion of oxygen, which weakens the coating and makes it easy to penetrate.

Stress-corrosion cracking

Stress-corrosion cracking, SCC, occurs when a material is corroding and exposed to repeated wearing and vibration (Davis, 2014, pp. 164-175). For SCC to occur there are mainly three factors that must be fulfilled; the construction must be in a specific environment that promotes cracking, the metallurgy in the current alloy must be susceptible to SCC and lastly the tensile stress, illustrated in figure 14, must exceed some kind of limit, which depends on application and alloy. Not all alloys are susceptible to SCC and their composition and microstructure have great effect on the cracking behaviour. Aluminium for example can be very weak against SCC when possessing a T6 heat treatment. However, if the metal undergoes a T73 or T76 overaging treatment it can almost become immune to this type of cracking due to the modification in the microstructure. The specific alloy is also of great importance regarding SCC resistance. Figure 15 show an aluminium profile that has been broken because of SCC.

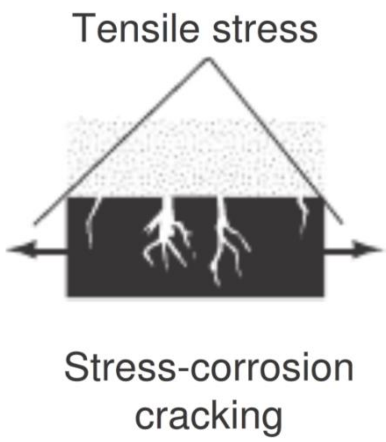

Figure 14 Schematic illustration of stress- corrosion cracking (Davis, 2014).

Figure 16 shows different factors which affect a metal’s susceptibility to SCC and how to avoid it in terms of mechanical, metallurgical and environmental factors. For example, to change a metal into a stronger alloy is not always better since a strong metal often is more brittle.

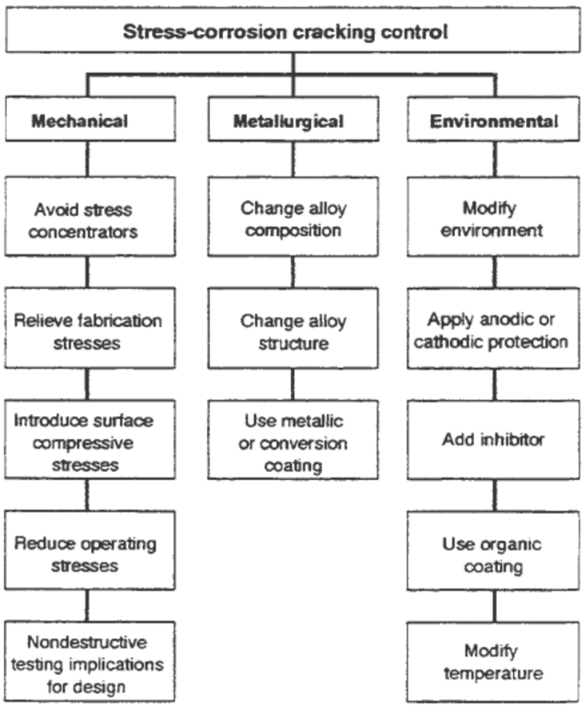

Figure 15 Factors that relates to stress-corrosion cracking control (Davis, 2014).

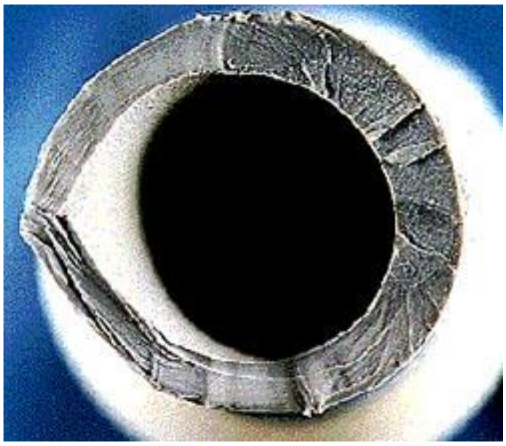

Figure 16 A case of SCC on an aluminium profile (Nasa, 2015).

Table 1 below shows some known cases of SCC for common alloys in a number of different environments. It shows that aluminium alloys has suffered from SCC in aqueous environments.

Table 1 Some environment-alloy combinations known to result in SCC

	Alloy system								
					Stainless steels				
Environment	Aluminum alloys	Carbon steels	Copper alloys	Nickel alloys	Austenitic	Duplex	Martensitic	Titanium alloys	Zirconium alloys
Amines, aqueous	…	X	X	…	…	…	…	…	…
Ammonia, anhydrous	…	X	…	…	…	…	…	…	…
Ammonia, aqueous	…	…	X	…	…	…	…	…	…
Bromine	…	…	…	…	…	…	…	…	X
Carbonates, aqueous	…	X	…	…	…	…	…	…	…
Carbon monoxide, carbon dioxide, water mixture	…	X	…	…	…	…	…	…	…
Chlorides, aqueous	X	…	…	X	X	X	…	…	X
Chlorides, concentrated, boiling	…	…	…	X	X	X	…	…	…
Chlorides, dry, hot	…	…	…	X	…	…	…	X	…
Chlorinated solvents	…	…	…	…	…	…	…	X	X
Cyanides, aqueous, acidified	…	X	…	…	…	…	…	…	…
Fluorides, aqueous	…	…	…	X	…	…	…	…	…
Hydrochloric acid	…	…	…	…	…	…	…	X	…
Hydrofluoric acid	…	…	…	X	…	…	…	…	…
Hydroxides, aqueous	…	X	…	…	X	X	X	…	…
Hydroxides, concentrated, hot	…	…	…	X	X	X	X	…	…
Methanol plus halides	…	…	…	…	…	…	…	X	X
Nitrates, aqueous	…	X	X	…	…	…	X	…	…
Nitric acid, concentrated	…	…	…	…	…	…	…	…	X
Nitric acid, fuming	…	…	…	…	…	…	…	X	…
Nitrites, aqueous	…	…	X	…	…	…	…	…	…
Nitrogen tetroxide	…	…	…	…	…	…	…	X	…
Polythionic acids	…	…	…	X	X	…	…	…	…
Steam	…	…	X	…	…	…	…	…	…
Sulfides plus chlorides, aqueous	…	…	…	…	X	X	X	…	…
Sulfurous acid	…	…	…	…	X	…	…	…	…
Water, high-purity, hot	X	…	…	X	…	…	…	…	…

X, known to result in SCC

Galvanic corrosion

When two different metals are in electrical contact and surrounded by an electrolyte the less noble metal tend to corrode whilst the more noble one is protected, as seen in figure 17 and 18, (Mattsson, Korrosion, 2015). This is an electrochemical reaction based on the fact that coupled metals have different levels of corrosion protection (Davis, 2014, pp. 125-126).

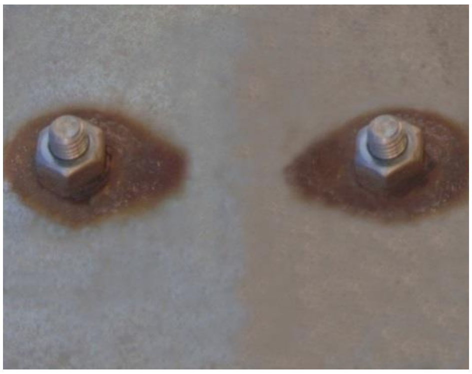

Figure 17 Example of galvanic corrosion as seen in the brown areas around the nuts (Wikimedia, 2015).

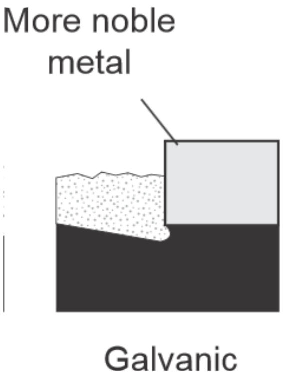

Figure 18 Schematic illustration of galvanic corrosion (Davis, 2015).

More theoretically this corrosion resistance is dependent on the metals electrode potential in electrolytic environments, more accurately shown in figure 19. The two metals differing potentials are what promote the ions to transfer from the anode, the less noble metal, to the cathode, the more noble metal. This results in the anode dissolving at an accelerated rate in the electrolyte. The differing electrode potential, the electrolytic environment and an electrical conducting path between the metals are all necessary to initiate galvanic corrosion.

Davis (2014, p. 129) states that the size of the anode relative to the cathode has a direct effect on the material's corrosion rate. He further explains that if the cathodic surface is larger than the anode there will be an undesirable outcome where the anodic surface will get a fast corrosion rate. If the roles are reversed then the corrosion rate of the anodic surface will decrease compared to the previous case.

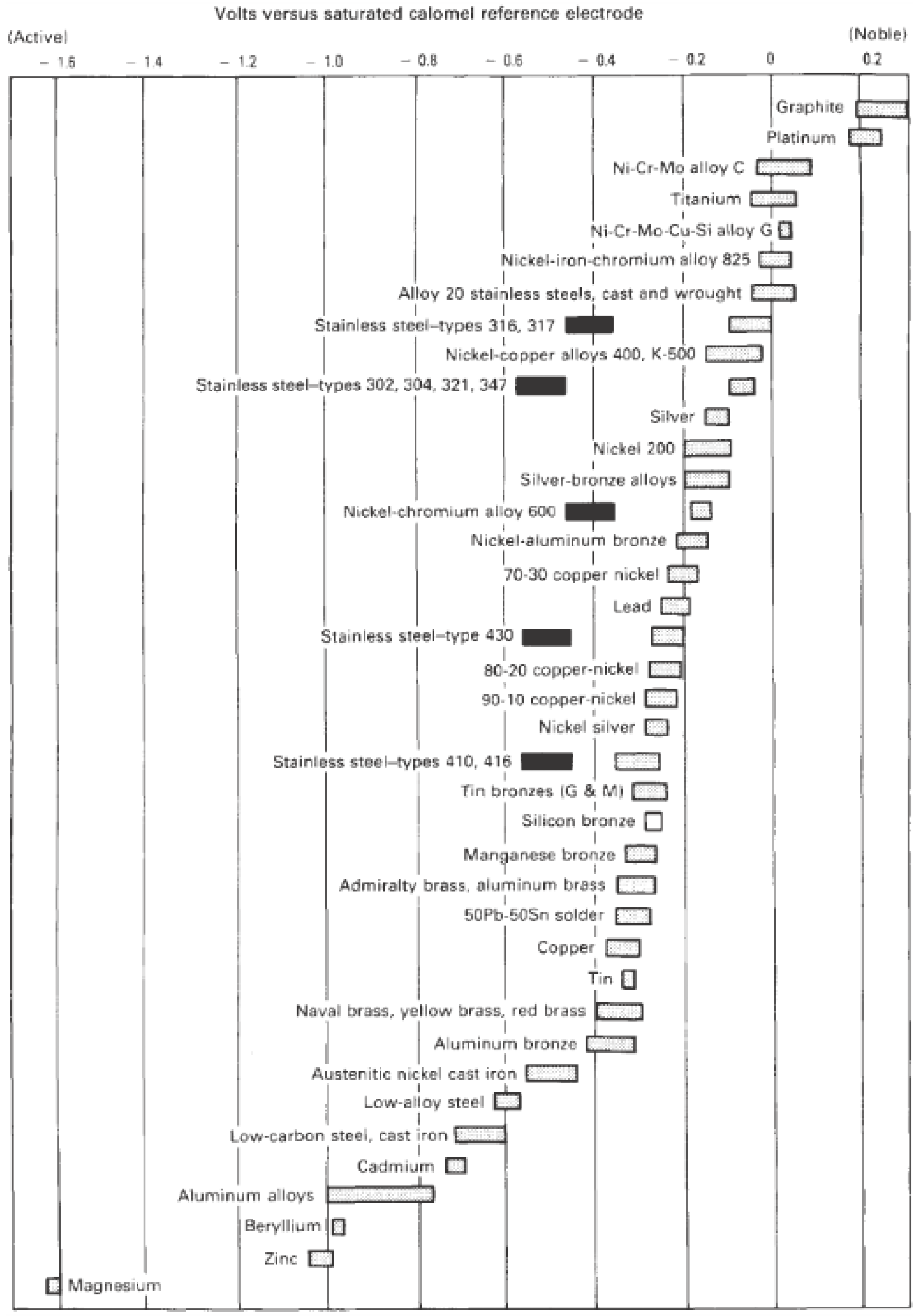

Figure 19 The galvanic series for metals in seawater (Davis, 2014).

General methods for corrosion prevention

According to Davis (2014, pp. 6-9) it can generally be said that there are five main methods for protecting a product from corrosion.

Material change

One relatively easy method to protect a product from corrosion is simply to replace the metal parts with non-metals which are non-conductive and will not corrode. If, however, a metal is needed then a more noble one could be used, such as palladium, platinum, gold, silver, titanium or stainless steel which are at the top of the galvanic series, see figure 19. For prevention of galvanic corrosion in a construction with two or more metals they should be chosen so that they are placed close to each other in the galvanic series. If not, the less corrosion resistant metal will corrode at a higher rate, especially if the less noble part is smaller in comparison to the more corrosion resistant metal.

Some alloys, so called passive metals, create an oxide coating on its own and if this coating is strong enough it could also work as corrosion protection. Stainless steel is an example of this phenomenon and is often a good option. These passive metals however, are not recommended to use when trying to avoid crevice corrosion. The reason is that in crevices it can occur a lack of oxygen, which is what the oxide coating needs to remain strong.

Coatings

If it is impossible to replace the metal with a non-metal, the material could instead be coated which prevents the electrolytes from reaching the metal. Generally there are two types of coatings, metallic and non-metallic. The metallic coating can consist of a more noble metal and take advantage of its corrosion resistance in relation to the metal it protects. It could also consist of a less noble metal and work as a sacrificial anode, whereas non-metallic coatings aim to completely isolate the protected metal from its environment. If coatings are used in constructions with at least two metals it is important that both the nobler and less noble metal are coated properly. If only the less noble one is coated it will become extremely vulnerable in areas where the coating is insufficient.

Passive metals create a natural oxide coating. Aluminium for example creates a 0.01μm thick layer of aluminium oxide, Al_2O_3. The coating can be improved by anodization which makes it harder and able to withstand wear better as well as granting an increased corrosion protection by using an electrolysis process (Karlsson, 2015).

Inhibitors

It is similar to coatings in how it is applied to the material but its function is different and is therefore often combined with coatings. While coatings separate the material from its environment, the inhibitor simply inhibit the corrosion by suppressing its rate. Either the inhibitor is merged with the coating or it works as a primer in case the coating would not suffice. Inhibitors could also be put in the surrounding electrolyte. The inhibitors often create a passivation layer that separates the corrosive substance to access the metal.

Cathodic protection

Another method to control corrosion is to use so called cathodic protection which means that the protected metal is connected to a sacrificial anode, a more active and easily corroded metal. For example, if a zinc detail, or any other less noble metal, is connected to a steel detail, the zinq will attract all corrosion and the iron will be protected. Other common materials used as sacrificial anodes are those placed lowest in the galvanic series, see figure 19, such as magnesium and aluminium.

It is also possible, with help from an external direct current source in shape of a rectifier, to create cathodic protection artificially. As figure 20 indicates, the rectifier in this case creates a strong anode with an electric current and makes it more active and “produces” electrons. Hence, from this the pipe is protected very efficiently but it should also be taken into account that this method is more expensive than most of the others.

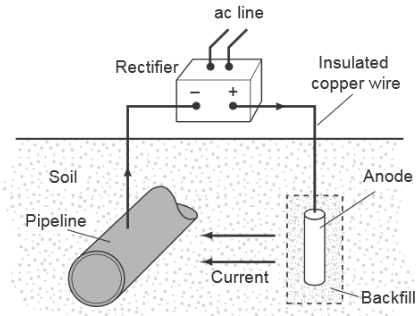

Figure 20 Schematic illustration of artificial creation of cathodic protection (Davis, 2014).

Design

When designing a product there are opportunities to eliminate shapes and areas where corrosion otherwise would thrive. Empty spaces and crevices are examples of areas that preferably are removed. Areas that continuously are exposed to load can encounter SCC which often can be avoided through a different design. Thin elements can for example be made thicker but there are also many other ways of spreading the load. Design can in this case also refer to how often maintenance is planned. If an area that probably will suffer from corrosion is detected then maintenance should occur more frequently. Threads in metal parts are especially weak against corrosion and the outcome of broken threads can be disastrous, they should therefore be avoided when possible.

If the threads are connecting two different metals in an electrolytic environment they are very vulnerable to galvanic corrosion. In those cases the metals can be separated by dielectric couplings such as plastics, ceramics or other non-conductive materials. Since electrons cannot travel through non-conductive materials the result will be that the circuit is broken and corrosion is prevented (Davis, 2014, pp. 133-134). Figure 21 illustrates a correct insulation of a bolted joint.

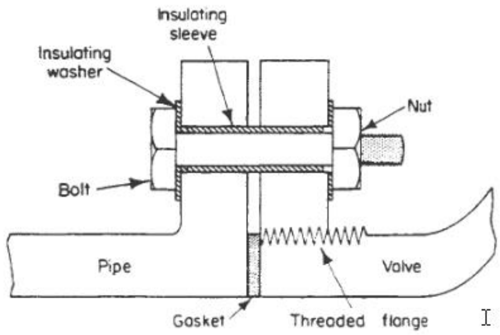

Figure 21 Schematic illustration of how to properly insulate a bolted joint (Davis, 2014).

3 Methods

In the following chapter the methods that were used throughout the project are described as well as how they were of assistance.

3.1 Feasibility Study

The project was initiated by a feasibility study in order to gather more information regarding components, existing solutions and to fully understand the difficulties areas. This is also done to uncritically show different technical solutions to avoid costly design and test validations based on false premises (Johannesson, Persson, & Pettersson, 2004, p. 88).

The study is focused on bearings, seals, permanent magnet generators, pressure compensating systems and corrosion. The result of the feasibility study regarding pressure compensating and corrosion is presented in chapter *4.1 Feasibility Study*. The result of the feasibility study regarding permanent magnet generators, bearings and seals are presented in appendix 2, 3 and 4 respectively.

3.2 SWOT Analysis

A SWOT identifies and maps the product's strengths, weaknesses, opportunities and threats. It shows where potential improvements can be found and also how it is affected by external and internal factors (Johannesson, Persson, & Pettersson, 2004, p. 82). It was used as a tool when describing the product in its current state in how it works, what it is made of and how it is produced.

3.3 Stakeholder Analysis

A method that lists all stakeholders that can have opinions about changes in the product (Johannesson, Persson, & Pettersson, 2004, p. 112). Stakeholders can for example be customers, departments, organizations or anyone that would be affected by the products design. The stakeholders are usually also good sources of information when making the development.

This analysis was made to clarify which parties and factors that had to be taken into consideration when starting the development.

3.4 Brainstorming

Brainstorming is a well-known method to use in product development when looking for new ideas and solutions on specific problems (Johannesson, Persson, & Pettersson, 2004, pp. 425-426). The point of the method is to generate as many ideas as possible by stimulating each group members creativity, combining ideas, and improving each other's ideas together as a group. The group usually consist of 5 - 15 people with different skills and experience and a session is usually about 45 - 60 minutes. Some basic ground rules are usually applied in order to have a successful session and are as following:

- Criticism is not allowed. All ideas are welcome and try not to judge and any idea as “right” or “wrong”. A critical review of the generated ideas will be conducted after the session.
- Quantity rather than “quality”. In order to increase the chance of some of the generated ideas being really good it is important that a number of ideas come up during the session. Also, one “bad” idea can during the session evolve and become a good one through association and combination with other ideas.
- Think outside the box. Just because an idea is unconventional it does not necessarily has to be wrong or bad. It has been shown that a rather strange or crazy idea may become a great idea by a little bit of modification.
- Combine ideas. Let the group combine arisen ideas and complement them throughout the session. New solutions can be a result of the combination of two ideas.

This method was used during the concept generation regarding each separated system as sealing, bearings, pressure compensation and corrosion prevention. The process and concepts were documented during the sessions by simple models or sketches to illustrate thoughts and ideas.

3.5 CAD

The concepts generated were constructed to early models in Catia V5 which is a software for creating 3D solid models. This software was used throughout all the remaining stages of the project for development of the concepts.

3.6 Pugh’s Decision Matrix

After generating a series of concepts a Pugh’s decision matrix was used in order to choose which concept was best suited for the application and to further develop (Johannesson, Persson, & Pettersson, 2004, pp. 133-135). The decision matrix is a well-known method where each and every concept are compared to a reference concept, in this case the products that are used today. The matrix shows clearly how the different concepts solve each function in comparison to the reference. Figure 22 shows an example of how a decision matrix can look like. The “+” and “-” indicates if a concept fulfils the function better or worse than the existing component while a “0” indicates that it fulfils the function by the same degree as the existing component.

Kriterium	Alternativ				
	1 (ref)	2	3	4	5
Önskemål A	DATUM	0	+	0	–
Önskemål B		+	+	+	+
Önskemål C		0	0	–	–
Krav D		0	–	0	0
Önskemål F		–	+	–	–
Summa +		1	3	1	1
Summa 0		3	1	2	1
Summa –		1	1	2	3
Nettovärde	0	0	2	–1	–2
Rangordning	2	2	1	4	5
Vidareutveckling	ja	ja	ja	nej	nej

Figure 22 A decision matrix according to Pugh (Johannesson, Persson, & Pettersson, 2004, p. 134)

3.7 Visualisation

The 3D models were rendered in the software Autodesk Showcase and edited in Adobe Photoshop CS6. This was done in order to visualize each concept in a distinct environment or highlight specific details.

4 Results

This chapter presents the result of the feasibility study followed by a specification of the final concepts and lastly the development process of the chosen concepts.

4.1 Feasibility Study

The feasibility study involved analysing the current design as well as creating a SWOT-analysis and a stakeholder analysis.

4.1.1 Current Design

The internal components of the front section of the nacelle addressed in this project are seen in figure 23. The turbine (1) is located in the front of the nacelle and is connected to a shaft (2). A mechanical seal (3), not shown in the figure, is placed around the shaft in order to keep sea water from entering the system and oil from leaking out of the system. Two ball bearings (4) stabilize the shaft and reduce shaft deflection. A gearless permanent magnet generator (5) converts the mechanical energy to electrical energy. The pressure compensator (6) is used in order to pressurize the system. The fairing (7) and the generator housing (8) encapsulates the internal components. All of these components will be further described in this chapter as *Internal design and components.* Along with this the system's corrosion resistance will be evaluated as well in *Corrosion resistance*.

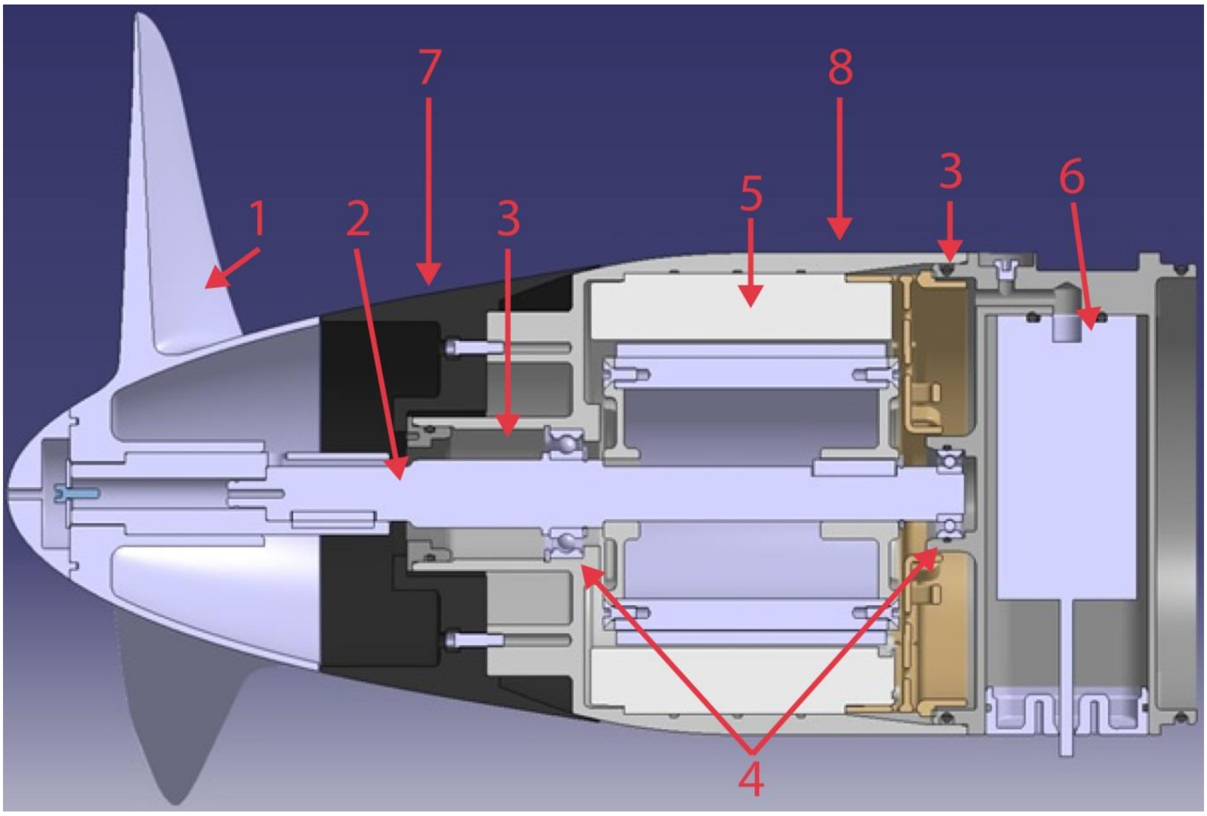

Figure 23 Section view of the front part of the nacelle (Andersson & Klamer, 2015)

Internal design and components

Below follows a more detailed analysis of each component evaluated in this project.

Seals

A mechanical seal, described in appendix 4, is used on the rotating shaft to shut out the seawater from the internal components and prevent the oil to leak out to the seawater. This seal works well today and just a small amount of leakage has been detected. The leakage has been accepted since the oil that leaks out is biologically degradable and it is of highest importance that the seawater does not leak into the system. O-rings, one is highlighted in figure 24, are used in the connection between nacelle sections. The sections are tightened together by screws, also shown in figure 24. This is a simple solution that has worked well in the purpose of keeping water and oil separated.

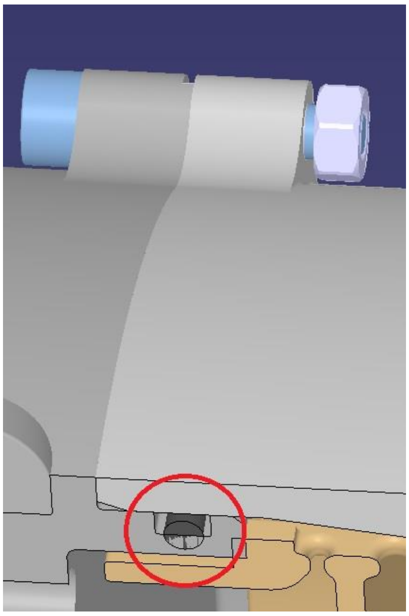

Figure 24 Sealing O-rings located between the nacelle sections, highlighted in the red circle (Andersson & Klamer, 2015).

Bearings

Two ball bearings are placed on each side of the generator, highlighted in figure 25. They allow the shaft to rotate with minimal friction and so the rotor in the generator. The bearings carry the forces created by the turbine, mainly axial, and have not shown any signs of fatigue in the tested prototype. It is the bearing to the left that takes up all axial loads while the smaller one to the right only creates stabilization and reduces any shaft deflection.

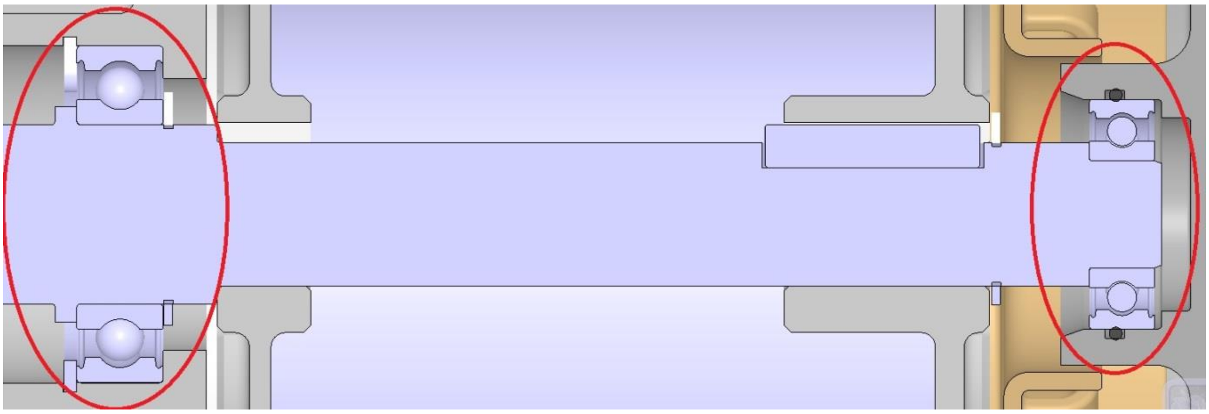

Figure 25 Section view showing the bearings supporting the shaft (Andersson & Klamer, 2015)

Pressure compensator

Minesto uses a pressure compensator from Tecnadyne model PC2X, see figure 26. This component uses a rolling diaphragm to transfer the ambient pressure and a spring to create an overpressure in the oil filled system. The over pressure generated by the PC2X is approximately 0.25 bar (Tecnadyne Products: Pressure Compensators, 2015). This is a simple and effective pressure compensator but it occupies too much volume in the application than desirable, see figure 27. The device needs to be exposed to the seawater to take hold of the ambient pressure, this also means that it has to be isolated in a separate section so that no seawater can enter the system. However, this leaves a lot of unused volume on both sides of the component as seen in figure 27.

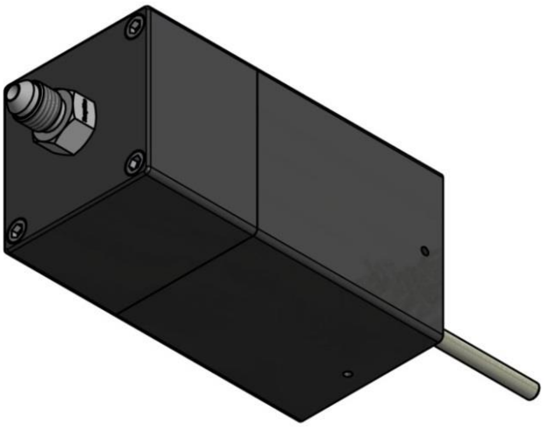

Figure 26 Pressure compensator model PC2X from Tecnadyne (Tecnadyne, 2015).

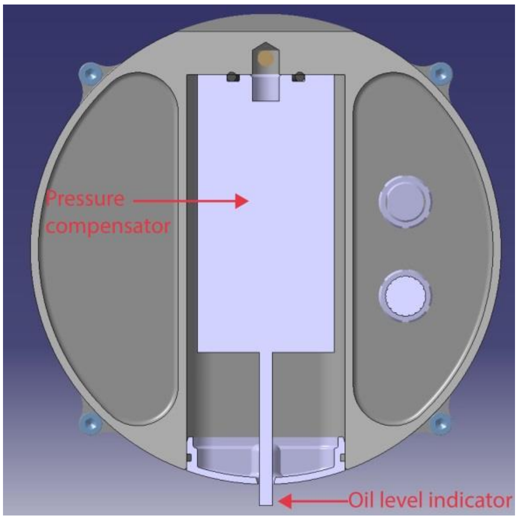

Figure 27 The pressure compensator occupies much volume on its own and its placement results in empty and unused spaces on each side of the device (Andersson & Klamer, 2015).

The system sections that are filled with oil are highlighted in figure 28. It is this section that the pressure compensator is connected to and pressurizes in order to establish an internal over pressure through the principle described in chapter *2.2 Pressure Compensation*. The pressure compensator contains an oil reservoir of approximately 60 ml to compensate for any leakage in the system.

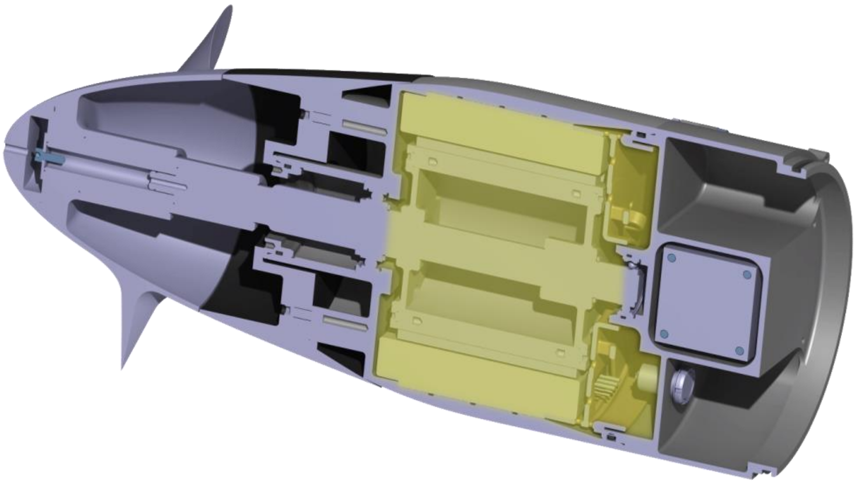

Figure 28 The yellow highlighted area illustrate the volume filled with oil in the generator housing (Andersson & Klamer, 2015).

Replenishment of oil into the generator housing

Leakage will in time cause the reservoir to be emptied which will require the system to be refilled during maintenance. The oil indicator, as seen in figure 27, is directly attached to the spring and diaphragm and so its position will tell how much oil is still in the system. The following steps describe how a refill operation is performed:

- A pump is connected to the vent port, see figure 29, and the air in the system is drawn out to create a vacuum.
- A coupling is then switched allowing oil to fill the system.
- The first two steps are repeated and the nacelle shaken a few times in order to reduce the amount of air in the system.
- The oil indicator is pulled out to release the rolling diaphragm from any pressure and allows it to be filled without any added pressure.
- As the indicator is held in its current position the vent port is closed.
- Once the vent port is closed the indicator can be released which adds the spring pressure to the system.

This is a relatively easy process since every component needed can be accessed from the outside of the nacelle and nothing needs to be disassembled. However, to reduce, preferably eliminate, air bubbles inside the system can be difficult but is of great importance in order to establish an almost incompressible oil system.

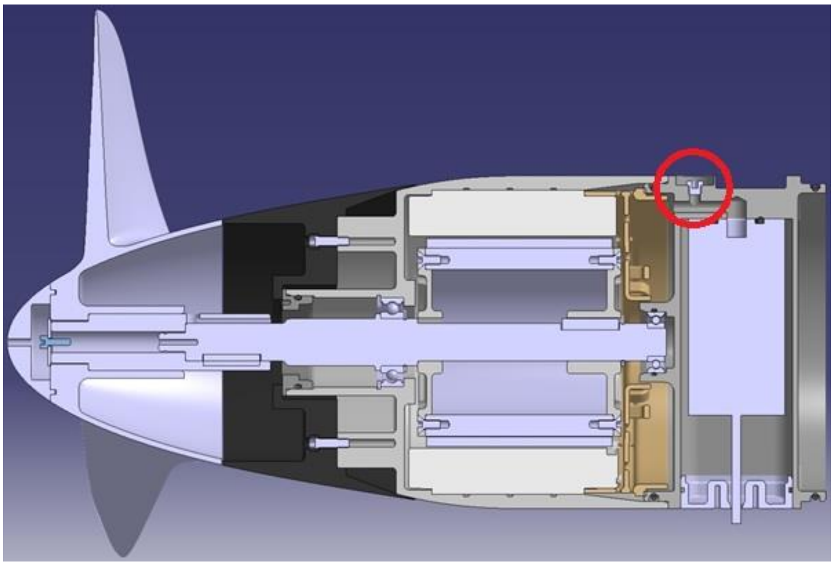

Figure 29 Section view of the nacelle displaying the vent port used during replenishment of the system (Andersson & Klamer, 2015)

Corrosion resistance

The nacelle shows signs of corrosion. Attempts to address this have been by using different types of anodizations on the aluminium nacelle and changing materials in screws. The corrosion is mainly located in the threads of the screw mounts that hold the different sections together as seen in figure 30 and 31. The consequences of this are that water leaks into the system and damages internal components.

The aluminium alloy used for the nacelle is aluminium 6082, an AlMgSi alloy. Generally aluminium has a good corrosion resistance because of its oxide coating but this has also been improved by using Tufram surface treatment, an anodization method, which improved the protective coating to approximately 50 μm (Andersson, 2015).

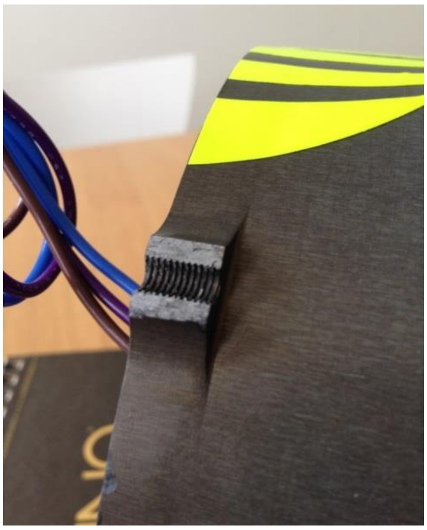

Figure 30 The image shows a screw mount that has cracked during testing (Andersson & Klamer, 2015).

Figure 31 The image shows another screw mount that has cracked (Andersson & Klamer, 2015).

Figure 30, 31, 32 and 33 shows a nacelle that has been part of the testing prototype. The nacelle show signs of corrosion and other damages on different areas. Even though it is evident that the nacelle is affected by corrosion after reviewing the system and studying the surfaces of the damaged component, it is more difficult to determine what type of corrosion it is suffering from. Various types of corrosion need different solutions applied in order to overcome the problem, it is therefore required to first determine which type of corrosion the nacelle is victim of. Tuveson-Carlström (2015), expert in corrosion and employee at Swerea, means that this is usually done by conducting field studies as well as laboratory testing. These tests usually review a series of factors such as pH-values, environment, time of exposure, material and many more depending on the application. This indicates how complex corrosion problems can be and that it require much time as well as resources to conduct a proper investigation.

Figure 32 Colour differences on the surface of the nacelle (Andersson & Klamer, 2015).

Figure 33 Scratchs and surfaces damages on the nacelle (Andersson & Klamer, 2015).

However, looking at the affected areas of the nacelle it is possible to generate a hypothesis of what type of corrosion it is affected by. Regarding the screw mounts of the nacelle the hypothesis is that it is affected by stress corrosion cracking, SCC. This is based on the factors listed below and not confirmed by any testing done by a third party such as Swerea.

- The screw mounts are submerged in seawater which is an environment that promotes cracking for the current aluminium alloy, see table 1 on page 11.
- The screw mounts are under static tensile stress which can initiate cracks and enable crack propagation.
- The aluminium 6082 is an alloy susceptible to SCC (Mhaede, Wollmann, & Wagner, 2008).

These three factors match the three factors described in chapter *2.3 Corrosion* which have to be fulfilled if SCC is to occur.

4.1.2 SWOT Analysis

After reviewing the current design a SWOT analysis was created to point out its strengths, weaknesses, opportunities and threats.

Strengths

- The current nacelle is well sealed by a mechanical seal and O-rings, thus reducing the risk of any seawater leaking into the system.
- The oil used in the system is biodegradable which reduces the risk of any environmental damage in case of a failure or leakage.
- The pressure compensator in combination with the fluid filled system eliminates the need of hard capsulation, described in appendix 1 and therefore saves material resources.
- Using aluminium together with oil provides good thermal conductivity for the system compared to air (The Engineering ToolBox, Thermal Conductivity, 2015).

Weaknesses

- Corrosion is a severe problem that mostly attacks the threads on screws and screw mounts.
- The oil filled system results in more friction for the generator and bearings which reduces the efficiency.
- Many unused volumes can be found throughout the product.
- There is only one vent port for oil refill which makes drain and fill during maintenance difficult.
- There is a leakage, even though it is small, where oil leaks out of the system into the environment.
- The manufacturing of the aluminium nacelle is a costly process where the whole detail is lathed from a solid block.
- The current design is not a flexible platform*.

* A flexible platform is a design which is open for transformation and allows components to be replaced in the future with ease.

Opportunities

- The current design has some unused volumes because of its hydrodynamic shape which can be used more efficiently to make the product more compact.
- The stress on some of the components is not too high which could allow the material to be replaced with something cheaper and possibly lighter.

Threats

- The harsh and aggressive environment can cause serious damages on the construction.
- The weight of the construction is today at its top limit which makes any material changes difficult.
- A change in the nacelle material could result in insufficient mechanical and thermal properties as well as it may not tolerate contact with oil or seawater.
- Design changes could result in comprehensive reconstruction on the product.

- It is still unclear of how the product affects the environment and vice versa over a longer time period.

4.1.3 Stakeholder Analysis

A stakeholder analysis was made to point out the key stakeholders of this project. At first an analysis for the whole system and industry was made to be able to list all stakeholders, see figure 34. This figure shows the stakeholders in every aspect and phase of the product and not necessarily only the stakeholders that affect this project. All of these parties are of importance for Minesto when developing their system, but for this project several will not be included. Hence figure 35 where only the stakeholders more relevant for this project are highlighted; owners, employees and subcontractors.

Figure 34 The image show several different stakeholders to the project (Andersson & Klamer, 2015).

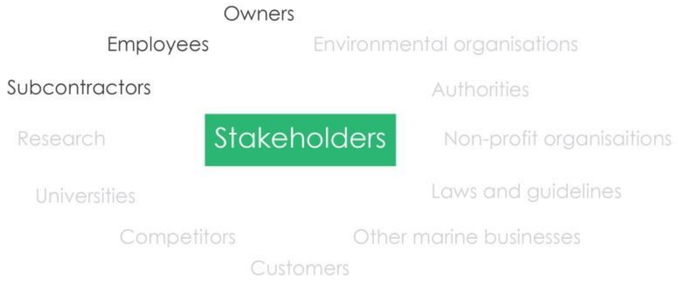

Figure 35 The image show the three most relevant stakeholders to this project (Andersson & Klamer, 2015).

This project is in cooperation with Minesto, the outcome of the project is therefore in their, as in owners and employees, interest since the aim of the project is to further develop their product. To ensure that their interests are met meetings with a supervisor from Minesto were conducted regularly. This also gave the opportunity to share their experiences and knowledge of the product and its use.

Subcontractors and employees in terms of manufacturing are also important to take into consideration. The product must be able to be manufactured and assembled as easy as possible.

4.2 Pressure Compensating Concept

In the following chapters the chosen concept for the pressure compensator is described as well as its development.

4.2.1 Chosen Concept “C-compensator”

The C-compensator is illustrated in figure 36 and is based on the existing PC2X used today but redesigned and relocated in the nacelle. It is placed in an unused area in the front of the nacelle, around the turbine shaft, see figure 37 and 38, and eliminates the whole section used for the existing pressure compensator today. This reduces the front part of the nacelle length from 431 mm to 348 mm, measuring from the top of the turbine head to the end of the nacelle, and saves approximately 19 % in axial length of the nacelle section addressed in this project, see figure 39.

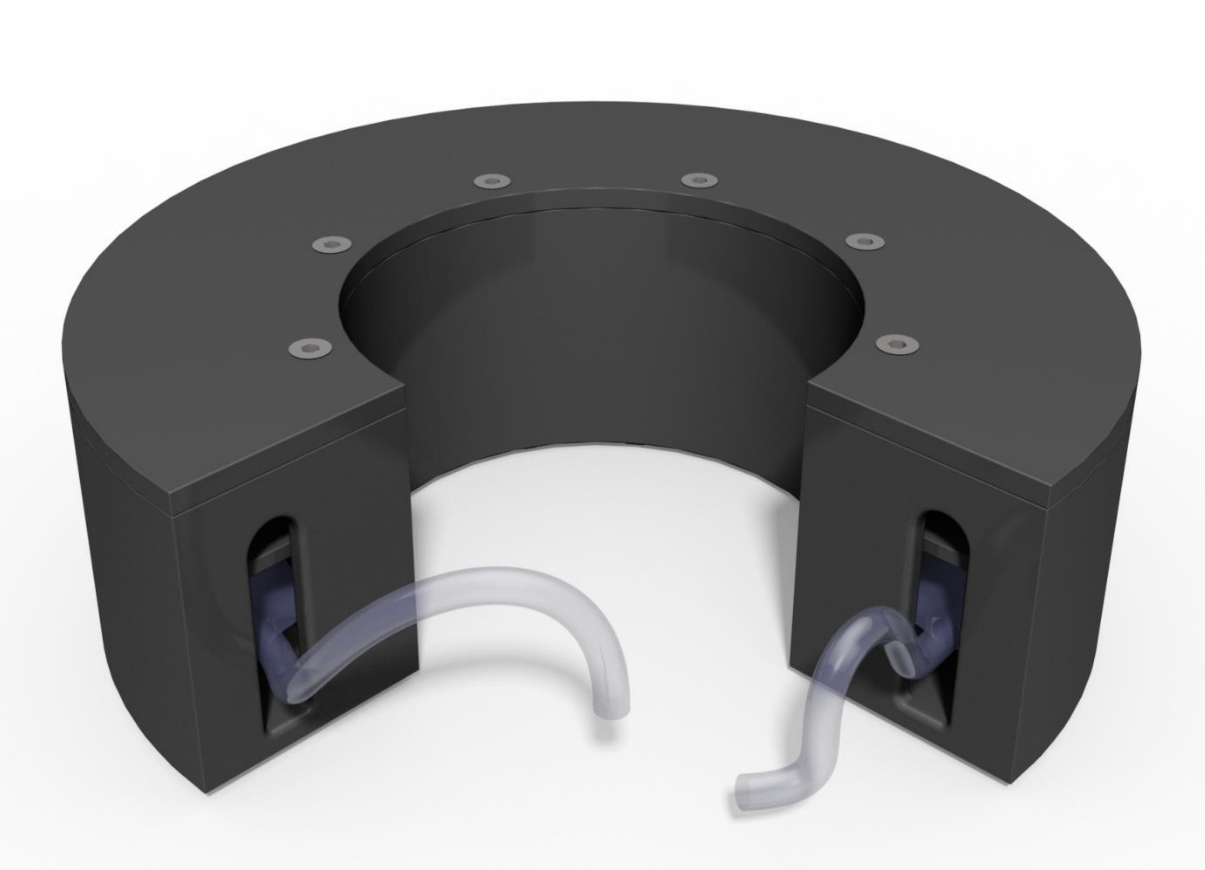

Figure 36 The final pressure compensator concept C-compensator (Andersson & Klamer, 2015).

Figure 37 The C-compensator placed in the front of the generator housing (Andersson & Klamer, 2015).

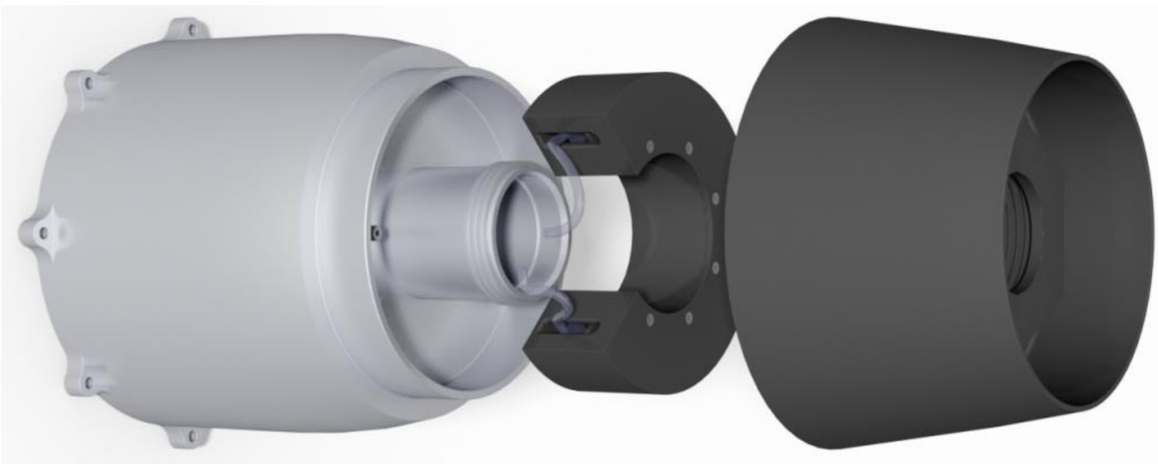

Figure 38 An exploded view of the generator housing, the C-compensator and the fairing (Andersson & Klamer, 2015).

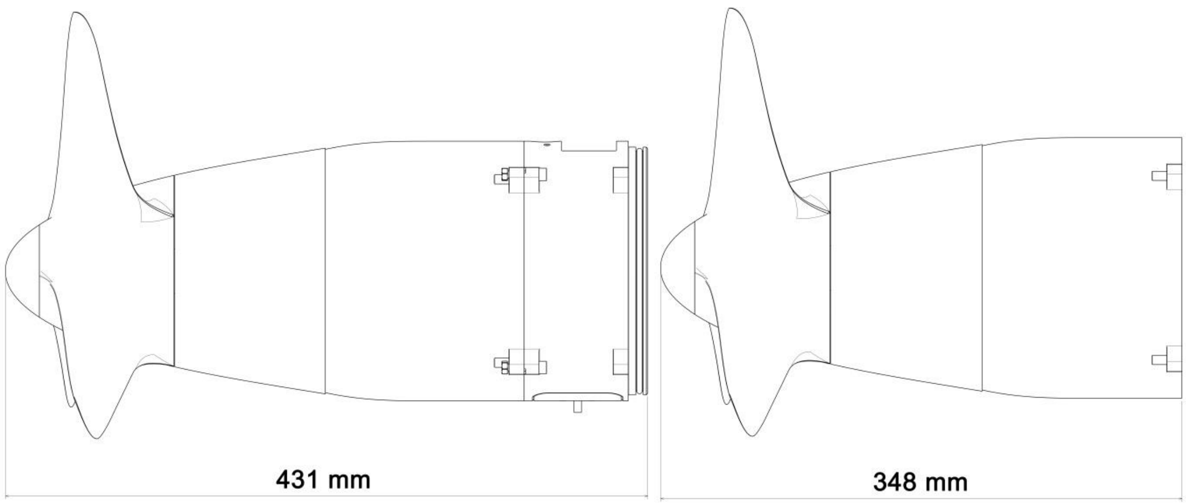

Figure 39 The nacelle is shortened as the section where the PC2X is located can be completely removed as displayed in the illustration (Andersson & Klamer, 2015).

Function

The C-compensator works similarly to the PC2X in many aspects. It adjusts the internal pressure by being exposed to the ambient pressure. The adjustment is done with an oil filled system and it creates a slightly higher internal pressure by a spring load. But there are some factors in the functions that differ and the design is completely changed. Inside the casing of the C-compensator a bladder, a pressure plate and six springs are placed, as can be seen in figure 40. The bladder is the component that through being exposed to the ambient pressure adjusts the internal pressure inside the system. The seawater reaches the bladder through the holes on the side of the casing. It also contains a reservoir of oil since the system is known to have some leakage. To ensure that this leakage is oil leaking out and not seawater leaking in, a spring load generated by the six springs act on the bladder which creates a positive Δp between the internal and external pressure. This leakage however, is very small and almost considered to be negligible. As also can be seen in figure 40 the bladder has two tubes. One that is connected to the system through a coupling and one that facilitates fill and drain procedures by creating a better flow.

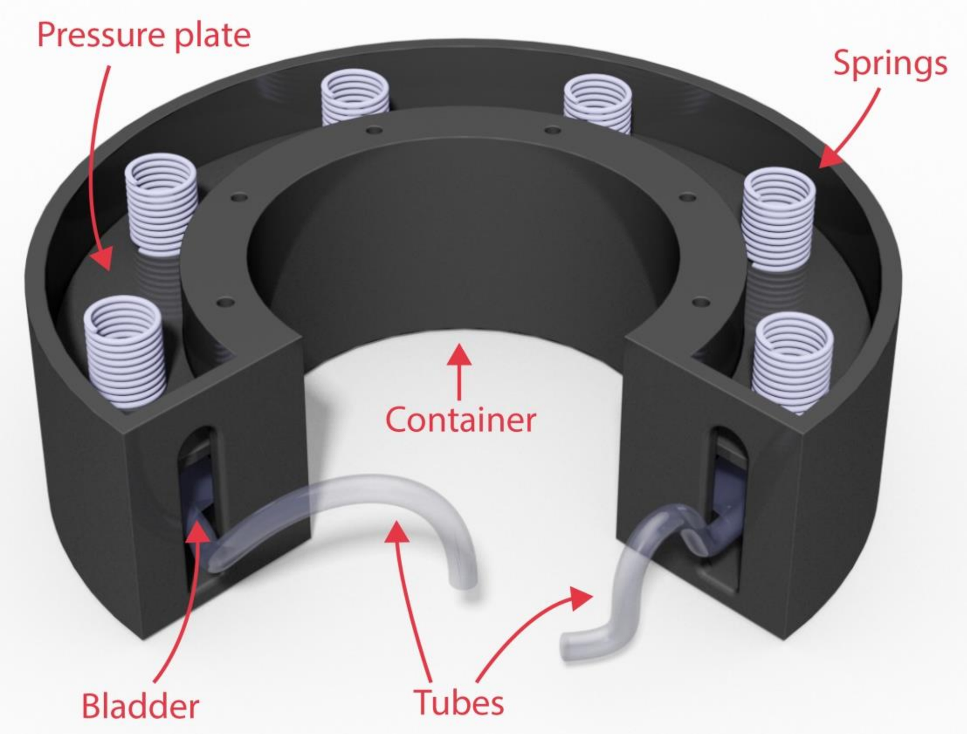

Figure 40 The C-compensator without the lid, exposing the internal springs and other components (Andersson & Klamer, 2015

Construction and assembly

The outer casing consists of two parts: a container and a lid, see figure 41. As can also be seen the casing has a circular shape with an extent of 270^{o}. The material of these parts and the pressure plate is polyoxymethylene, POM. POM is a strong semicrystalline thermoplastic with good mechanical properties and works well in constructions (Ek, 2015). In combination with this POM also has good chemical and moisture resistance which is an important factor for this application. It has been used in other components throughout the nacelle as well as in the existing PC2X and is well suited for this application. The use of a non-metallic material also reduces the risk of corrosion. The holes located on the outside of the container serves the purpose of letting the tubes run freely as the bladder is filled and emptied as well as they let seawater reach the bladder which applies the ambient pressure. The container and the lid are held together by a series of M3 screws located on the inner wall of the casing. On the inside of the casing the bladder, springs and pressure plate are located.

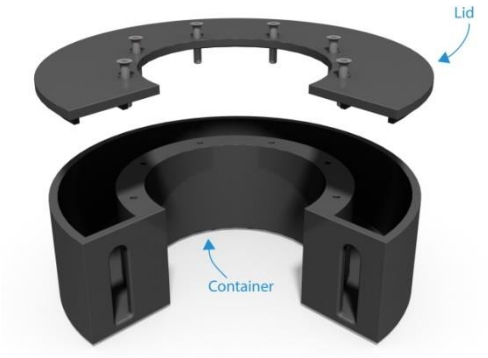

Figure 41 The C-compensator's external components (Andersson & Klamer, 2015).

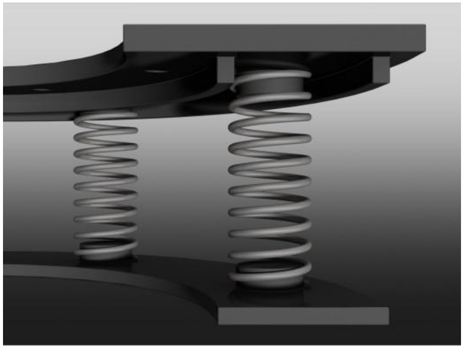

Figure 42 The springs are placed on pins on the lid and the pressure plate (Andersson & Klamer, 2015).

The springs are placed on six spring pins on both the inside of the lid and pressure plate, see figure 42. These pins hold every spring in place and the pressure plate ensures that the load from the springs is evenly spread across the bladder.

The C-compensator must be assembled before placed in the nacelle. When placing the C-compensator the tube is first connected to the inlet coupling and then the compensator is put in place around the shaft. Once it is there it will be locked in place by two ribs in the nacelle which stops it from rotating when the fairing is screwed down, shown in figure 43. When the fairing is screwed down it holds the compensator in place and prevents it from moving.

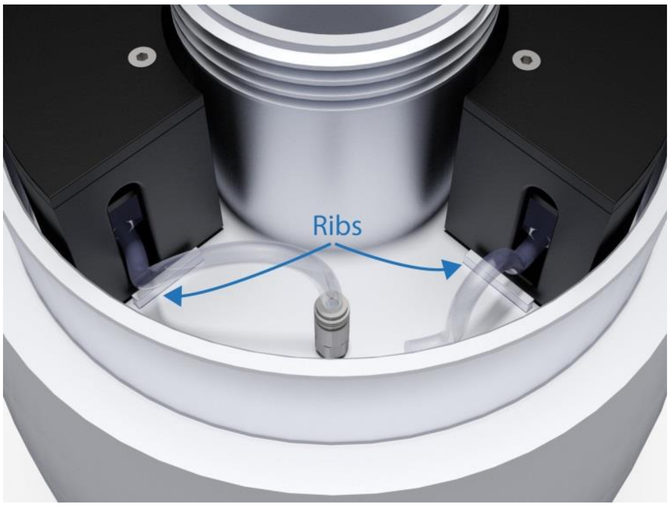

Figure 43 Two ribs stop the compensator from rotating in the nacelle (Andersson & Klamer, 2015).

Underneath the C-compensator there is a rib pattern protruding from the bottom, see figure 44. This pattern serves the purpose to prevent any crevice corrosion from occurring. As described in chapter *2.3 Corrosion*, this type of corrosion happens in tight areas where there is no flow of fluids or where depletion of oxygen occurs. The ribs lift the C-compensator 1 mm from the nacelle and allow the seawater to flow freely between the two components.

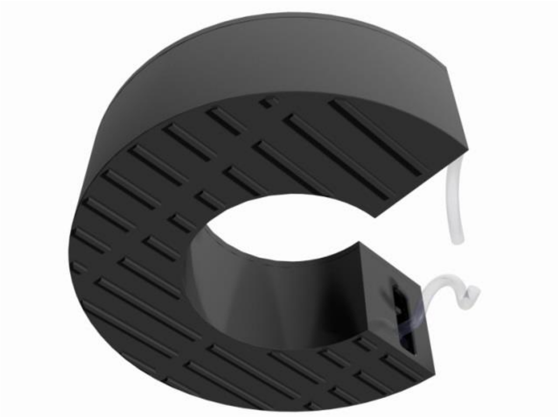

Figure 44 Ribs on the bottom of the compensator reduce the chance of crevice corrosion (Andersson & Klamer, 2015).

Springs

The six springs in this application are accurately placed in parallel across the pressure plate to ensure an even spread of the load on the plate's A=0,005 m^2 surface and on the bladder, see figure 45. When choosing springs it was important that they generated a suitable load and that they had the right dimensions. In chapter *1.3 Criteria*, it is stated that an overpressure of approximately 0.2 bar is desirable. A spring that fulfils this is Lesjöfors' SS 2387 1x10x35.5 cat.no. 2931, found in appendix 6, which has the following characteristics, compare figure 46:

Figure 45 The image shows how the pressure plate is located above the bladder as well as how the springs are located (Andersson & Klamer, 2015).

D_t = 1 mm (wire thickness)
D_m = 10 mm (mean spring diameter)
L_0 = 35.5 mm (unloaded spring length)
L_n = 12.4 mm (minimum working length)
c = 1.2 N/mm (spring rate)

δ_1 = 5.5 mm (minimum spring deformation)
δ_2 = 23 mm (maximum spring deformation)

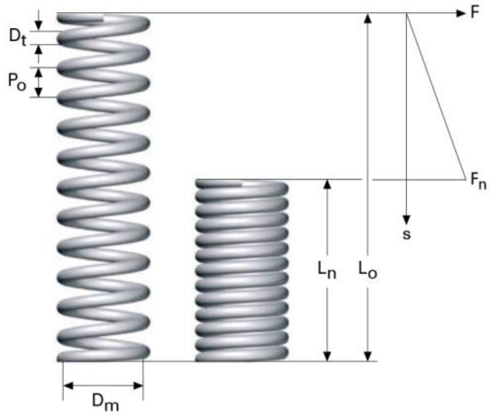

Figure 46 A visual illustration of spring variables (Lesjöfors, 2015).

The spring will be compressed by $\delta_1 = 5.5$ mm when mounted in the casing and by δ_2 = 23 mm when the bladder is completely filled. The corresponding total forces F1, F2 generated by the springs and the oil pressures P1, P2 can then be calculated as described in appendix 7. The results of these calculations are summarized below.

Variable	Value
F_1	62.6 N
F_2	165.6 N
p_1	0.125 bar
p_2	0.331 bar

As can be seen these springs generate an average pressure of 0.228 bar which is enough and meets the criteria of an average internal overpressure of 0.2 bar. The material of these springs however, is not suitable for seawater applications for longer periods of time, but it is considered to be tolerable for this concept. In a further development it would be necessary to find springs with similar characteristics but with a different material.

Bladder

Due to the harsh environment the bladder used in this concept is made of ether based polyurethane, TPU. This material is very resistant to chemicals and hydrolysis which makes it a good option when dealing with both oil and seawater as in this application, (Swerea, 2015). Since the bladder will be exposed to relatively low pressure differences the material thickness can be as thin as 200 µm (Petersson, 2015). This thickness makes the bladder more ductile and it can more easily adapt to the shape of the casing. The bladder is designed to contain an oil reservoir of 63 ml.


Figure 47 A close up of the welded seam around a tube of a plastic bladder (Andersson & Klamer, 2015).

The bladder is made of two plastic sheets welded together with the tubes welded in place between the layers as in figure 47. The tubes have a diameter of 3 mm to connect to a KD1-M3-A coupling from Festo.

Design modifications of original parts
In order to make the C-compensator fit inside the system modifications of the nacelle and the fairing were necessary. These modifications are described below.

Generator housing
The screw mounts that held the fairing in place are removed and replaced with threads on the smaller cylinder in the centre. It is on these threads the fairing is screwed onto instead, see figure 48. In order to fit 5 thread turns of standard M56 screw threads with coarse pitch the centre cylinder is extended by 10 mm (SMS, 1990). The removal of existing screw mounts made it possible to widen the outer wall and create more space around the shaft. On the bottom where the C-compensator is placed two ribs can be found which keep the compensator in place and prevent any rotation, see figure 49. In that same bottom a hole is placed which is where the coupling for oil supply is attached. The modifications of the outer screw mounts which connect this front section to the next section of the nacelle are described in chapter *4.3.1 Chosen Concept*.

Figure 48 A perspective view of the modified generator housing (Andersson & Klamer, 2015).

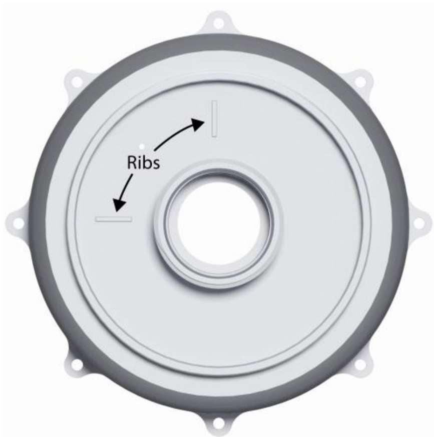

Figure 49 A front view of the modified generator housing (Andersson & Klamer, 2015).

Fairing
The changes made on the fairing are only on the inside since it was preferable to preserve its hydrodynamic shape on the outside. Figure 50 shows a section view of the fairing and figure 51 shows it from above and in both of them it can be seen that the screw holes are removed. Instead M56 threads are placed on the inside to match the threads on the nacelle. The wall on the inside of the fairing is modified to fit the outer wall on the nacelle. On the top in figure 51 the circular wall is changed into a hexagonal nut shape with the size of a M56 nut. This enables the possibility to fasten and tighten the fairing with a socket wrench or a torque wrench. A hole is placed on the top as well to ensure that water will get through to the bladder.

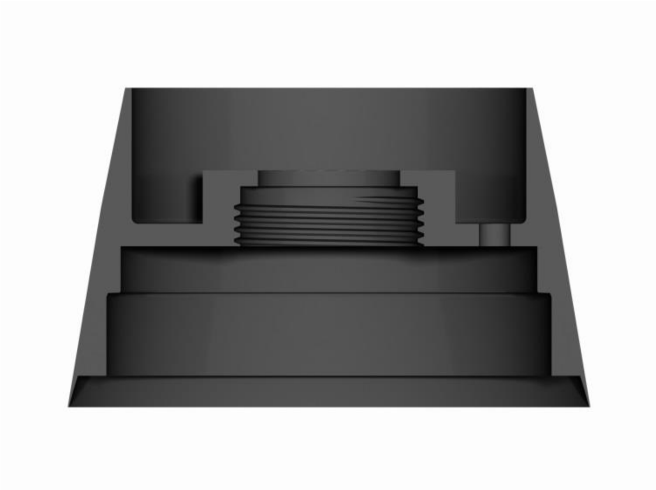

Figure 50 A section view of the modified fairing (Andersson & Klamer, 2015).

Figure 51 A top view of the modified fairing (Andersson & Klamer, 2015).

Replenishment of oil into the generator housing

Modifications are made to facilitate fill- and drain operations of the system. The addition of an extra tube to the bladder is a detail which simplifies such operations. This tube in combination with the old port at the back of the nacelle creates a flow through the system which, when tilting the nacelle, makes it easier to fill the system with oil and remove air. The following steps describe the general idea of how to fill the system with oil.

- Make sure that the tube is connected to the inlet coupling on the nacelle properly.
- Connect the other tube to a ball vent coupling, a pressure gauge and then to the refilling device.
- Open the vent port at the back of the nacelle, to let air out when the oil is filling the system.
- Tilt the whole nacelle so that the one port not connected to the refilling device is at the highest point for easier removal of air.
- Open the ball vent and begin to pump oil into the system.
- When the system is nearly full oil it will start to leak out of the upper vent port. When a steady flow of oil is flowing from the upper port and no air bubbles can be detected, close the upper vent port.
- The system is now filled with oil but the bladder in the C-compensator is still empty because of the pressure from the springs.
- Proceed to pump oil into the system to fill the bladder. As the bladder starts to fill it will compress the springs inside the pressure compensator. This will make the pressure rise inside the system as seen on the pressure gauge.
- When a pressure of approximately 0.33 bar is reached the bladder is filled completely. This can also be seen by looking at the height of the pressure plate through the groove on the short side of the compensator.
- Close the ball vent coupling, remove the pressure gauge and place the tube in the nacelle.
- Screw down the fairing and make sure that no tube is stuck in between.

The C-compensator does not have a distinct indicator of how much oil remains in the bladder. If however, the turbine and fairing are removed during maintenance it is relatively easy to see the location of the pressure plate and therefore determine the amount of oil as described in figure 52.

Figure 52 The oil level in the compensator is indicated by the height of the pressure plate. The left image show a full bladder while the right image illustrate an empty bladder (Andersson & Klamer, 2015).

4.2.2 Early Concepts and Their Development

Before the final concept was chosen several concepts and ideas were produced and developed. In the early stages of the project sketches and simple models were used to illustrate ideas and different pressure compensating methods.

Pressure compensation through membranes

In figure 53 several sketches are shown where the idea was to use membranes in walls or cross sections to separate the system from its environment and naturally transfer the pressure difference. Since the membrane material is elastic it will move inwards into the product when pressurized and press against the oil to compensate for the outer pressure.

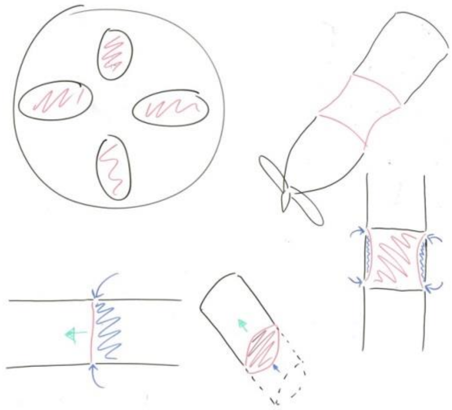

Figure 53 Several early sketches of pressure compensation by using membranes. The membranes are shown in red and the surrounding water in blue (Andersson & Klamer, 2015).

The different membrane locations lead to different advantages and disadvantages. By placing the membrane in the outer nacelle wall the use for an extra device which only purpose is to pressure compensate would be eliminated. Instead the wall would transfer the pressure differences at the same time as it holds the system together and act multifunctional. This would both reduce the number of complex components in the product as well as save volume. But since the membrane material is not a construction material it would most likely need a comprehensive reconstruction and was considered to cause trouble with the hydrodynamics.

By placing the membrane in a cross section these two problems are somewhat avoided but does not however, save the same amount of volume. The illustrations in figure 54 show further developments of the concepts P1.1, P2.1 and P2.2. Concept P1.1 illustrates one way of placing the membranes in the wall and since that wall in particular is protected by the black plastic fairing it does not affect the products hydrodynamics. It uses a space that otherwise stands empty and saves approximately 19% in axial length of the front section but requires a difficult reconstruction of the products nacelle.

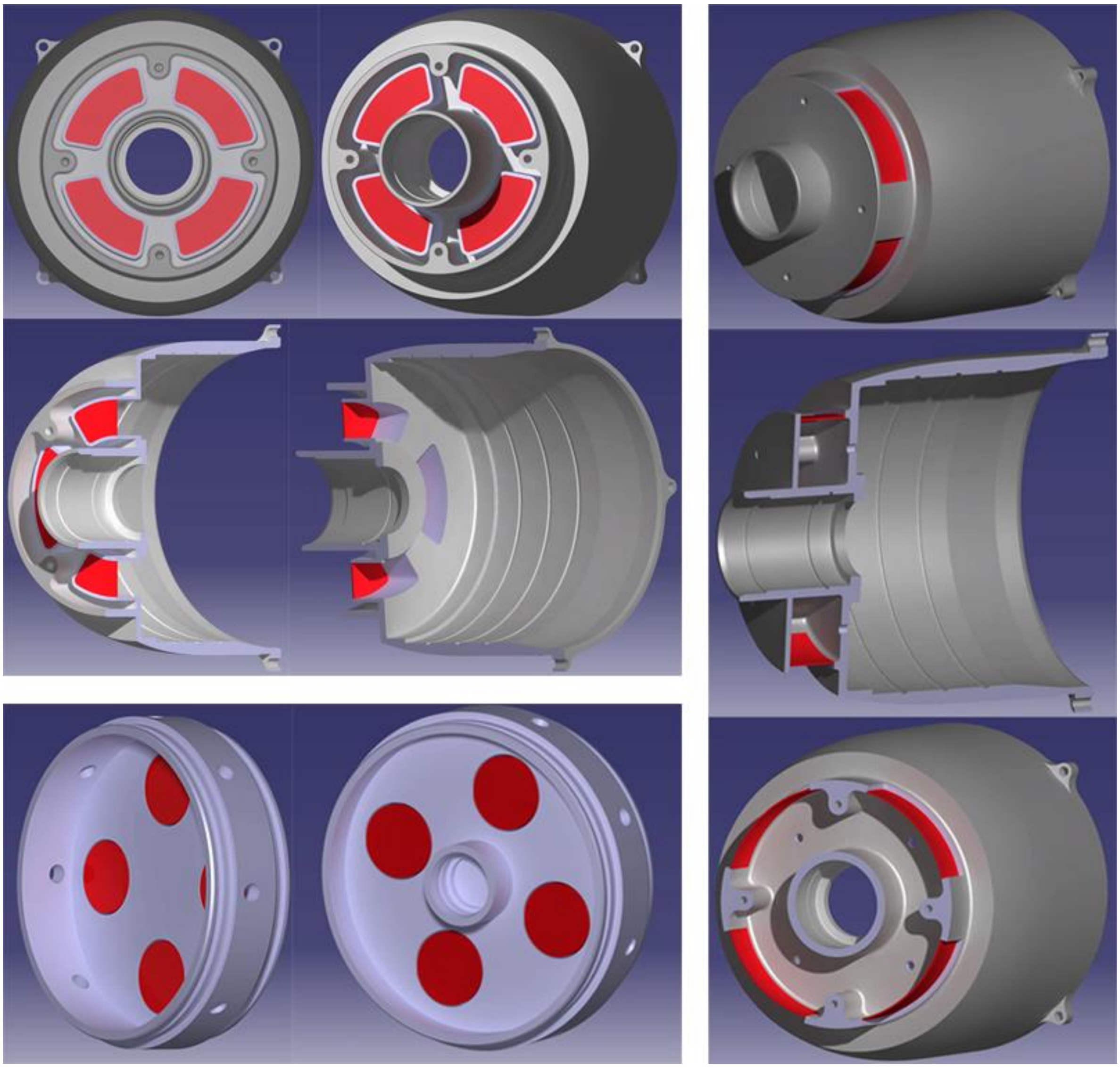

Figure 54 Several renderings of membrane concepts, the membranes are shown as red in the images. Named as following: Top left " P2.2", bottom left "2.1" and the right one "P1.1" (Andersson & Klamer, 2015).

The other concepts show two ways of applying membranes in cross sections where P2.1 is a separate component which is attached to the rest of the system and is relatively easy to produce and saves approximately 13% in axial length of the front section of the nacelle. P2.2 is harder to produce and is similar to P1.1 regarding reconstruction and volume efficiency.

Pressure compensation by relocating the current component

Another idea to solve this was to simply reuse the current method by having a unit filled with oil, preloaded by a spring and exposed to the surrounding water and give it a different design or placement. Figure 55 shows an early concept that would be placed in the nacelle and surround the rotating shaft. A few concepts were developed from this idea as well and in figure 56 three very early models showing their appearances and placements are illustrated.

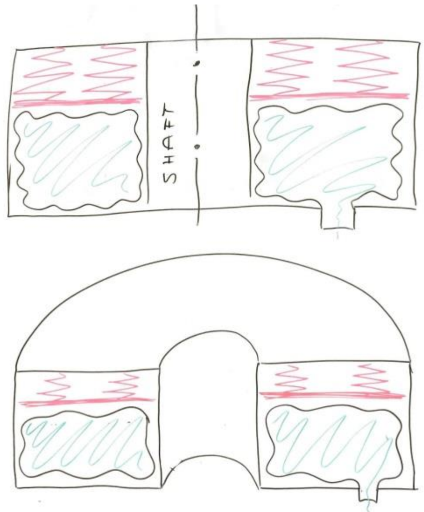

Figure 55 An early sketch of a pressure compensator that could be placed around the rotating shaft. The oil is shown in green and the preloaded spring mechanism in red (Andersson & Klamer, 2015).

P3.1 is a whole section that would be attached to the nacelle in the same place where the current pressure compensator is placed. It consists of an outer container to hold the unit together, a bladder containing an oil reservoir connected to the system with a tube and a spring loaded plate to push on the bladder. It saves approximately 13% in axial length of the front section of the nacelle. P3.2 and P3.3 are two very similar concepts and differ only in size and shape. P3.2 was the original idea and works in the same way as P3.1 but is hollow in the centre to be able to surround the rotating shaft. P3.3 is an upgraded version of P3.2 and uses the outer areas more effectively. The overall advantage with these concepts compared to the ones using membranes is that the technology exists, it is tested and it is proven to work in similar applications.

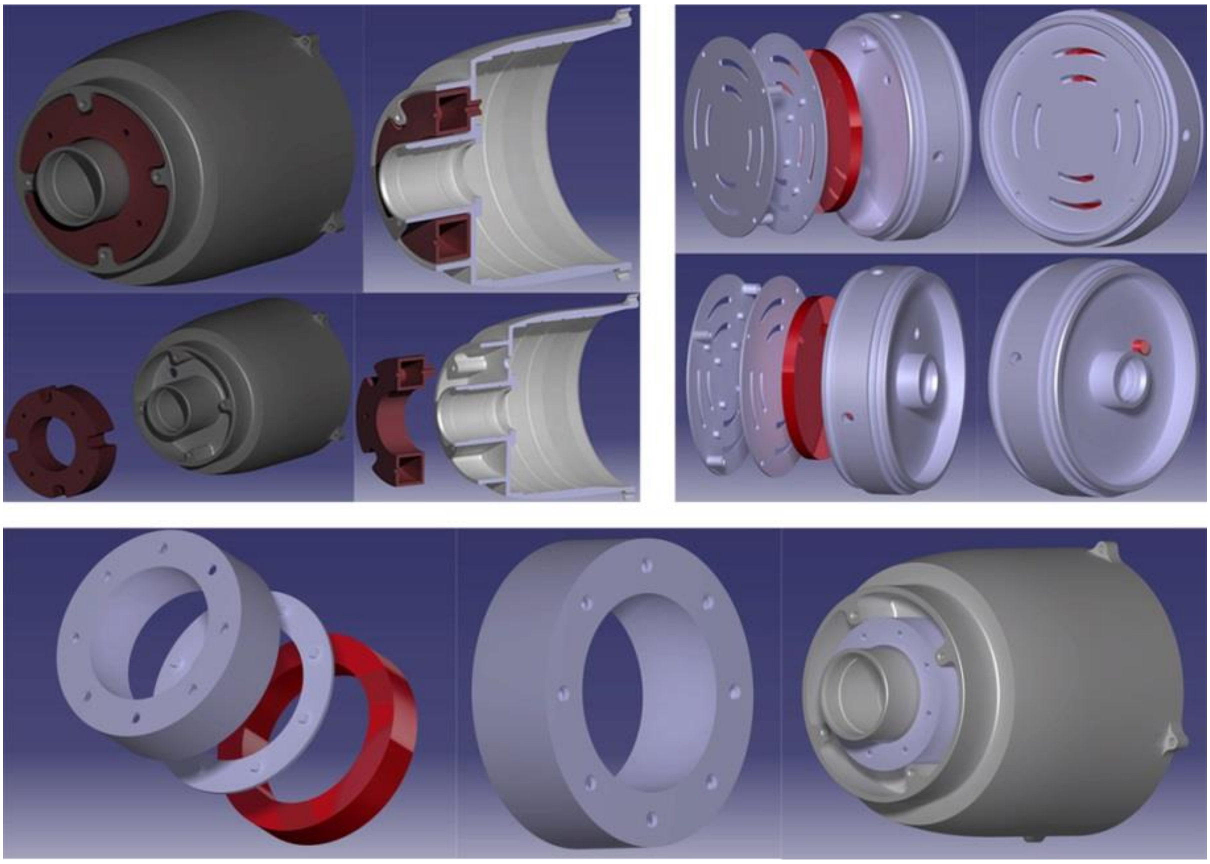

Figure 56 Concept developments rendered. Named as following: Top left "P3.3", top right "P3.1" and bottom concept "P3.2" (Andersson & Klamer, 2015).

Pugh's decision matrix

When comparing the concepts to each other and deciding which one to develop further Pugh's decision matrix was used. The result is presented in table 2.

Table 2 A Pugh decision matrix was used to decide which concept to further develop (Andersson & Klamer, 2015).

	Weight Value		Concepts					
Function		Ref	P1.1	P2.1	P2.2	P3.1	P3.2	P3.3
Volume saved	5	0	+	+	+	+	+	+
Refilling	4	0	0	0	0	0	0	0
Installation	2	0	-	-	0	-	+	+
Oil volume	3	0	-	-	-	+	0	+
Manufacturing	1	0	0	+	+	+	+	0
Σ-			-5	-5	-3	−2	0	0
Σ0			2	1	2	1	2	2
Σ+			+5	+6	+6	+9	+8	+10
Net value			0	+1	+3	+7	+8	+10
Ranking			**6**	**5**	**4**	**3**	**2**	**1**

As can be seen in the columns to the left in the table the highest rated functions were volume savings, refilling possibilities and how much oil the concept could contain. The concepts using membranes got the worst rankings, mostly because of their inability to contain oil reservoirs. It was therefore decided to put all these three aside and focus on the other functions. P3.1 was ranked as third best due to estimated complications during installation.

In the matrix it can be seen that all the concepts are more volume efficient compared to the reference concept. What does not show however, is exactly how much volume each concept saves. Concept P3.1 saves approximately 13% in volume compared to the existing compensator, but this is not as much as concept P3.2 or P3.3 which saves approximately 19%. The concepts P3.2 and P3.3 were the two top ranked concepts and are in fact very similar, this indicated that their function, construction and placement in the nacelle has potential. A problem with this placement though is the small space around the shaft in the front part of the generator housing which put high demands on the design in order to make the components fit in without compromising on the function.

Further development

The concepts P3.2 and P3.3 were chosen for further development which aimed to combine the two and create a component that would work practically. The main areas that had to be specified were attachment and assembly, materials, spring selection and bladder type. The dimensions of all these are essential if the concept is to work properly.

Attachment and assembly

How the pressure compensator would be placed and attached in the nacelle was difficult to specify due to, as mentioned earlier, the lack of space in the specific area. Figure 57 shows an idea where the pressure compensator's lid is threaded onto the rest of the components. The whole compensator is then attached to the nacelle through screws and the screw mounts on the nacelle.

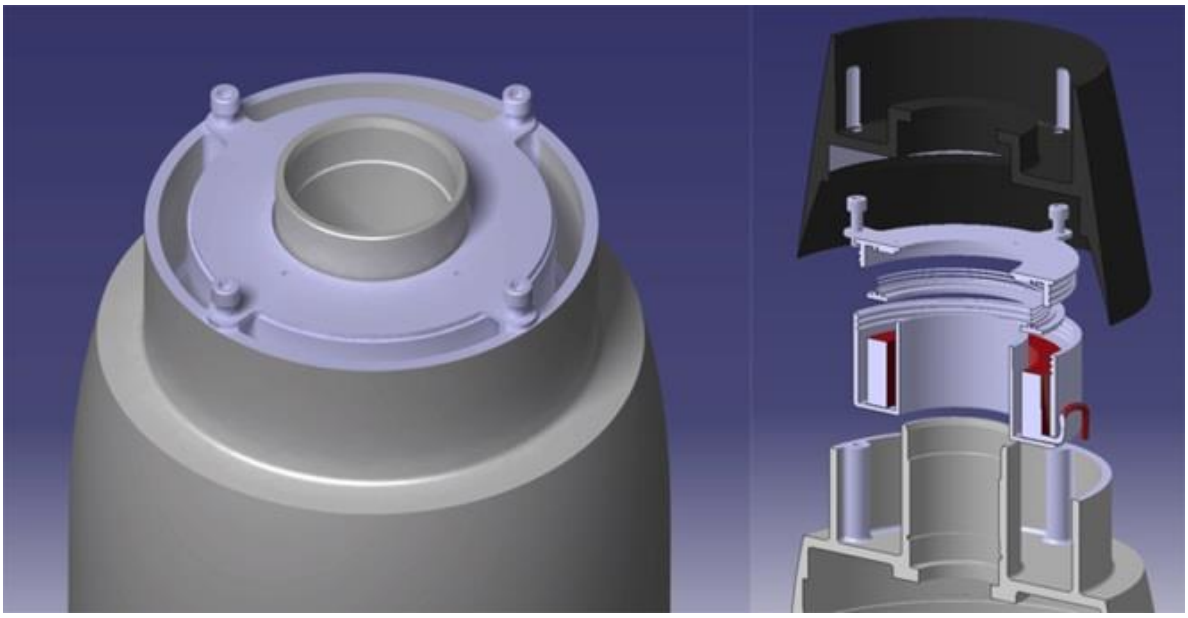

Figure 57 Left image show a concept of how to place and lock the compensator in the nacelle. The right image show an expanded section view of the whole concept (Andersson & Klamer, 2015).

Figure 58 shows a similar idea where the screw mounts have been moved towards the centre of the nacelle and are placed on the inside of the pressure compensator. Both these concepts would work practically but it was considered that the compensator did not need to be screwed into the nacelle and that the screw mounts occupied unnecessarily much space. Also the coupling needed to connect the bladder to the generator housing which was difficult to fit in the limited space. The mounts were removed and it resulted in the assembly method described in chapter *4.2.1 Chosen Concept* which created more space for the pressure compensator and also simplified the placement of the coupling.

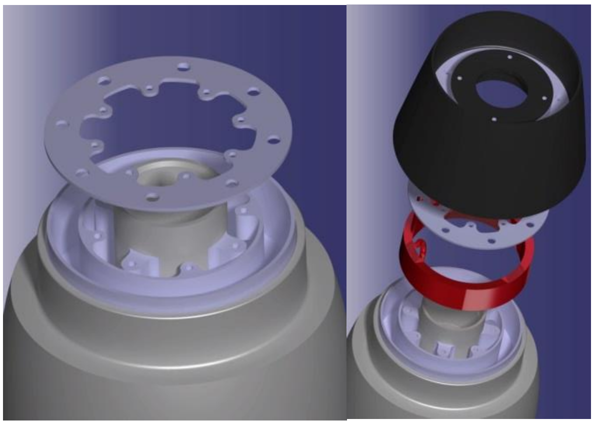

Figure 58 Another concept of how to place and lock the compensator in the nacelle. The right image shows an expanded view of the whole concept (Andersson & Klamer, 2015).

Spring selection

When a helical spring suited for the application was chosen its characteristics were essential in order to establish the desirable over pressure. It was discussed whether a single spring or several small parallel springs would be best suited. It turned out to be difficult to find a fitting spring in the larger size, the one that would surround the shaft, due to L_n and D_t could not be met relative to the given force F_n and so it was decided to use several smaller parallel springs instead. It was also discussed however a spring with a spring characteristic generating a more constant force could be used, such as a wave or a disc spring. But this was considered to not be necessary for this application.

Housing material
When a material for the pressure compensator's lid, container and pressure plate was chosen all metal options were screened out. The reason for this was to reduce the possibilities for corrosion and also because a more lightweight material was preferred, such as polymers. The pressure compensator that is used today, Tecnadyne's PC2X, uses POM as housing material which has proven to work well in marine environments. It was therefore decided to use POM polymer plastic as material for the compensator housing.

Bladder type
The factors that were of importance when choosing a bladder type was choice of material, shape, how it reacts to pressure and how it behave when compressed. The bladder material had to be resistant to seawater and oil for longer periods of time without suffering from any hydrolysis or swelling. The shape of the bladder was important since the bladder had to fit inside of the container. A more complex shape of the bladder would also make it more difficult and expensive to manufacture. The most simple bladder type is flat when empty and cylindrical when filled. If this type of bladder was to be used it had to be made of such a material that allowed it to be ductile and able to adapt to a circular shaped container. The bladder had to be able to withstand the pressure differences between the seawater and the oil filled system. Lastly it was important how the bladder behaved when it was being emptied of oil. Preferably it should collapse in a controlled way to avoid it to twist itself or cause any increased friction. This could be achieved by using bellows or a rolling diaphragm. However, the limited space in the container made it difficult to fit such bladders and the manufacturing cost would also be increased. Therefore a cylindrical bladder was chosen for the concept.

4.3 Corrosion Prevention Concept

The following chapter describes the chosen concept for prevention of corrosion, based on the hypothesis which states that the screw mounts suffer from SCC as described in chapter *4.1.1 Current Design*, as well as its development.

4.3.1 Chosen Concept

To prevent SCC the design showed in figure 59 is chosen to be used. As can be seen, this design has an increased number of screw mounts, 8 instead of 4, which decreases the tensile stress on each mount. The screw mounts are also made larger, from 9 mm to 12 mm in diameter, illustrated in figure 60, to further spread the load over each mount. Another difference is that the internal threads in each mount are removed and instead the screws go through the mounts and are tightened with nuts as illustrated in figure 61.

Figure 59 Left: The original generator housing. Right: The chosen concept for corrosion protection, with the increased number of screw mounts (Andersson & Klamer, 2015).

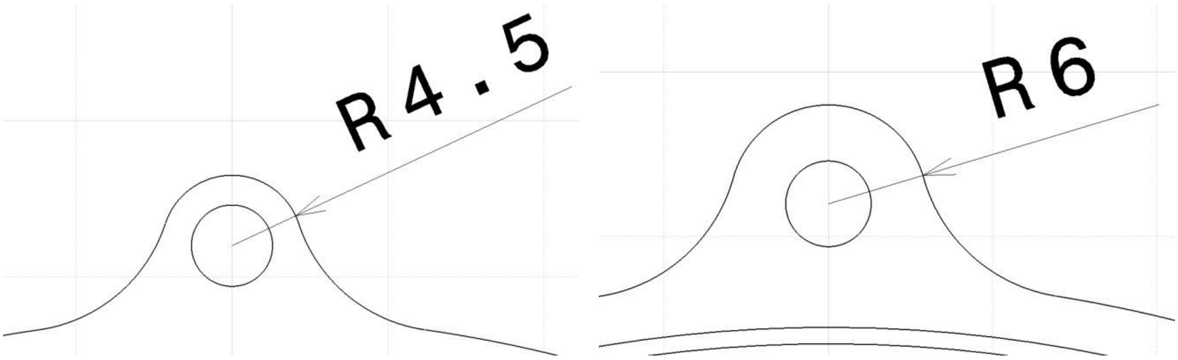

Figure 60 The image shows how the radius of the screw mounts has been increased from 4.5 to 6 mm. The right image illustrates the chosen concept. (Andersson & Klamer, 2015).

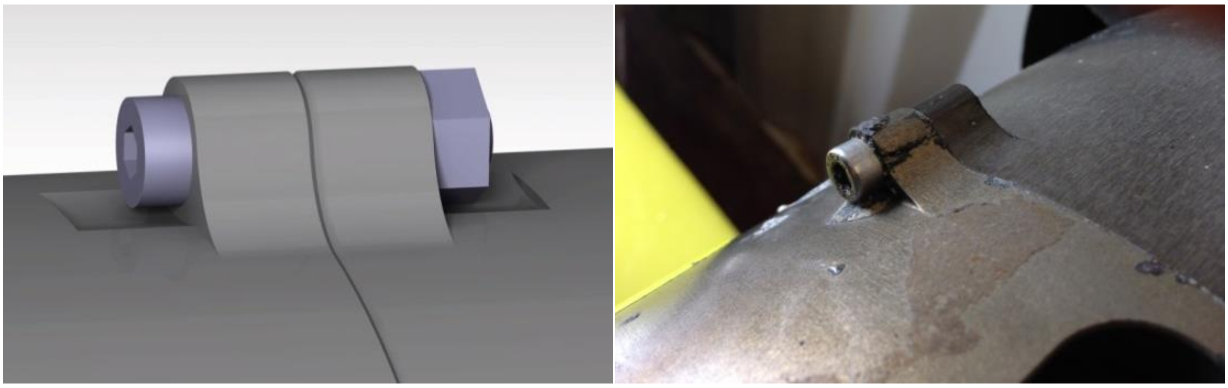

Figure 61 The left image shows how the screw is tightened with a nut instead of internal threads as in the right picture (Andersson & Klamer, 2015).

This is merely a design proposal aiming to reduce the corrosion in the screw mounts of the nacelle and further testing is required to verify that it actually works. When conducting such tests there are some general factors and methodologies that should be taken into consideration.

- Environment - The testing should be conducted in an environment that represents the real conditions as well as possible. This means that it should be done at the same location, at the same depth and undergo similar movements and operations.
- Time - The time of the tests should be representative for the life span of the nacelle. During the tests, regular checks and documentation should be done so that its progress could be followed more thoroughly. The time of such tests could be accelerated by doing them in more concentrated lab environments but with the risk of receiving a more inaccurate result.
- Different prototypes should undergo tests at the same time to show their differing behaviour under the same circumstances.

4.3.2 Earlier Concepts and Their Development

Corrosion is often a very complex problem and also very difficult to avoid in a marine environment. The first step is often just to determine which type of corrosion the application is suffering from and then which key factors that causes the corrosion. The following concepts described in this chapter were part of the development of the final concept choice. More concepts for prevention of other corrosion types based on the feasibility study are found in appendix 5.

Material

The driving force of galvanic corrosion is the difference of the electrode potential in different metals and alloys. This is displayed in figure 19, the galvanic series, page 12. The use of same materials, or materials close in the galvanic series, in several components was therefore positive in order to reduce the effect of galvanic corrosion. This however, turned out to be difficult to apply since different components needed different material properties. The use of same material throughout several components could therefore lead to insufficient properties in some components and a defective construction.

To evade this problem it was possible to isolate the metals from each other. Since the construction proved to be especially weak in the screw mounts a non-conductive tube could be placed between the screw and the screw mount as in figure 62 and 63. The downside of this concept was the increased area of crevices, which could lead to an increased chance of crevice corrosion.

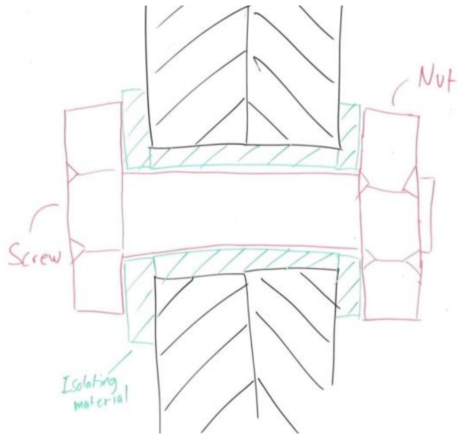

Figure 62 A sketch of how to prevent galvanic corrosion (Andersson & Klamer, 2015).

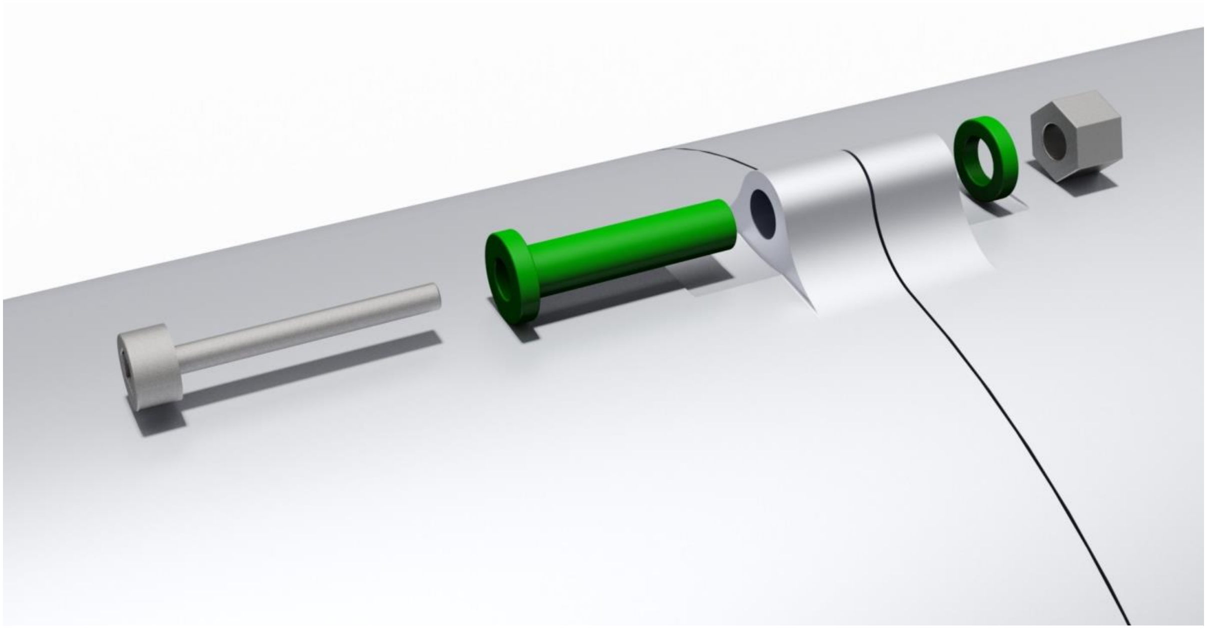

Figure 63 A rendered image of how to isolate different materials in the screw mounts (Andersson & Klamer, 2015).

Redesign of the section joints

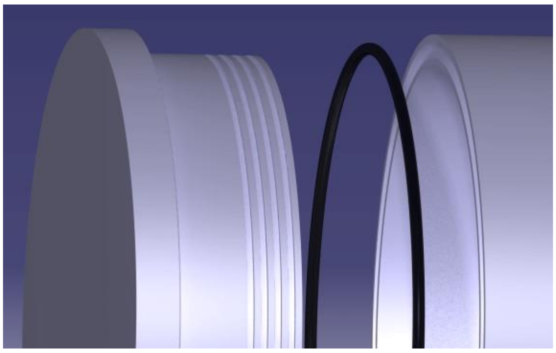

Figure 64 A rendering of a concept of redesign of the section joints (Andersson & Klamer, 2015).

The screw mounts placed on the outside of the nacelle proved to have a negative effect on the nacelle's hydrodynamic properties, creating a more turbulent flow. The mounts had also shown to be weak spots for corrosion, as described in chapter *4.1.1 Current Design*. A concept was therefore to reconstruct the joint between the nacelle sections as in figure 64 and remove the mounts completely. As can be seen in the figure threads were placed on the inside of the nacelle and the two sections were screwed together. An O-ring would seal the crevice and isolate the threads from seawater. In addition this would also improve the hydrodynamic properties of the nacelle. The downside of this concept was that the internal wiring would become twisted as the sections were screwed together and was therefore not chosen for any further development.

As it was a request from Minesto to retain the outer screw mounts since they had proved to work well, despite their negative impact on the hydrodynamics, it was decided to develop the mounts further as described in chapter *4.3.1 Chosen Concept*.

5 Conclusion and Discussion

The C-compensator concept showed improvement in areas where the current pressure compensator, PC2X, was insufficient. The main project aim was to make the nacelle more compact and volume effective which this concept has. Using the C-compensator the front part of the nacelle's axial length was reduced by approximately 19% since it only occupied an area in the nacelle which otherwise stood empty. Its function was quite similar to the current compensator, PC2X, which points to that the new concept would work as well.

What differed the compensators from one another was their shape and placement. The C-compensator was placed in the front of the nacelle and around the rotating shaft. The PC2X was placed in the back of the nacelle and had the shape of a cuboid. This new placement of the C-compensator allowed the nacelle section with the PC2X to be removed which reduced the nacelle's length. Another advantage of this was a weight reduction of the nacelle. The weight was declared to be at its peak on the current product and so weight reduction was also a goal to achieve with the C-compensator. The casing material in the C-concept was the same as in the PC2X, polyoxymethylene, POM, which is a strong plastic well suited for this application. Regarding the refilling process there were both pros and cons with the new design which should be reviewed more closely if the concept is to undergo further development. The addition of a second tube enabled a refilling process with improved flow and simplified the removal of air bubbles. The problem was that the C-compensator was placed inside the fairing. This implies that both the fairing and the turbine had to be removed before any refilling could be done. The PC2X could be accessed directly from the outside of the nacelle which was considered to be better. The PC2X also showed an indication of how much oil was still in the reservoir which was something that the new concept lacked. As described in chapter *4.1.1 Current Design* this indicator could also be used to remove the spring loaded pressure when the system was filled which was an advantage the new concept lack.

The review of the corrosion problems showed what a complex problem corrosion was and that every case needed thorough examinations and long-term testing. Every concept generated needed to undergo testing in a representative environment before any decisions could be made. These methods were not available in this project due to a lack of resources in terms of both time and tools. The concepts in this project were therefore based on a hypothesis made of visual examinations on models and documentations in combination with accessible information from previous studies and reports.

The concept developed to prevent SCC could be considered to impair the hydrodynamic flow of the nacelle. However, the benefit of having a product that did not leak or corrode was considered to outweigh the drawbacks of the concept. If the concept would be taken into further development some adjustments of the mounts could be made in order to improve the hydrodynamics.

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Figure 28: Andersson & Klamer (2015). *The yellow highlighted area illustrate the volume filled with oil in the generator housing* [Illustration].

Figure 29: Andersson & Klamer (2015). *Section view of the nacelle displaying the vent port used during replenishment of the system* [Illustration].

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Figure 32: Andersson & Klamer (2015). *Colour differences on the surface of the nacelle* [Photograph].

Figure 33: Andersson & Klamer (2015). *Scratchs and surfaces damages on the nacelle* [Photograph].

Figure 34: Andersson & Klamer (2015). *The image show several different stakeholders to the project* [Illustration].

Figure 35: Andersson & Klamer (2015). *The image show the three most relevant stakeholders to this project* [Illustration].

Figure 36: Andersson & Klamer (2015). *The final pressure compensator concept C-compensator* [Rendered image].

Figure 37: Andersson & Klamer (2015). *The C-compensator placed in the front of the generator housing* [Rendered image].

Appendix 1: Pressure Compensation with Hard Shell and Encapsulation

Hard shell

With an enclosed hard shell concept the components within will not be subjected to pressure cycling, even though the system as a whole will be subjected to a various pressure depending on the operating depth (Mehnert, 1972, pp. I-1). It is often necessary to use this concept for electronic circuitry and other sensitive components in order to obtain a stable system with good reliability.

The case is hermetically sealed and the components inside the shell often operate in air or an inert gas at atmospheric pressure (Mehnert, 1972, pp. xii-xiii). The surrounding shell must be designed to sustain a pressure exceeding the one of the planned operating depth. In order to maintain and inspect the enclosed system the shell needs to be able to be opened and closed using bolts, flanges and seals. The material used for the hard shell is usually high-strength steel which add cost and weight to the system as a whole. Heat removal is one problem associated with the hard shell concept as heat generating sources must be tied firmly to the walls as well as electrically insulated from it. This adds to the complexity of the concept.

Mehnert (1972, p. xiii) further means that the hard shell concept is often used in shallow submerges but is generally considered impractical when it comes to deep ocean operations and if rotating shafts penetrations into the ambient ocean environment are required. The frictional losses in a “zero leakage” system with high-pressure seals and thrust bearings would most likely be too great.

Encapsulation

In order to protect components from a harsh surrounding environment one could choose to completely encapsulate the component in a massive amount of material such as epoxy resin (Mehnert, 1972, p. xii). This is the standard technique used by the electronics industry in order to protect components and circuitry in a humid environment. This type of complete encapsulation will work as electrical insulation and environmental protection as well as a good thermal insulator. The downside of this technique is therefore heat transfer related but also as the materials used in the component and as the insulation are not always fully compatible.

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Appendix 2: Permanent Magnet Generators

Permanent Magnet Generators

An electric generator is designed to convert movement into electricity by taking advantage of electromagnetic induction. Electromagnetic induction is created because an electric charge in the presence of magnetic field in motion, or vice versa, will experience a force in a direction perpendicular to the magnetic field lines as well as the direction of the movement (von Meier, 2006, pp. 85-87). In a conductive material, usually electrons in a wire, these charges becomes an electromotive force (emf) that produces a voltage or a potential drop along the wire which causes an electronic current to flow. A generator is therefore used to obtain a current in a conductor as a result of mechanical movement, succeeding in conversion of energy from a physical form into electrical energy. In this way a generator is the opposite of an electronic motor which converts electronic energy into mechanical energy of motion. Since many generators and electronic motors are such similar devices they can also be operated either way, a generator can be operated as a motor and vice versa. However the design of a given machine should be optimised for its intended use in order to achieve the best performance possible. The major aspect of the design is the geometrical configuration which often distinguishes the many variations of specialized generators.

How it works

Permanent magnetic generators, *PM generators*, is using permanent magnets, usually made by rare earth elements, to create strong magnetic fields (Littmarck, 2012). These magnets are placed on the rotor or the wheel inside a stator, which is made of material with high relative permeability (the degree of magnetization of a material in response to a magnetic field), which is coiled with wire, see figure 1. When the rotor is set in motion the magnets, and therefore their magnetic fields, revolves inside the stator and as they pass the coiled stator a current is induced. The magnets are often spaced out evenly around the rotor which causes the strength of the *emf* to fluctuate up and down as the rotor revolves. This continuous flux induces the current into the stator wire. The voltage output is determined by the type of magnets used, the coil and the rate of revolutions.

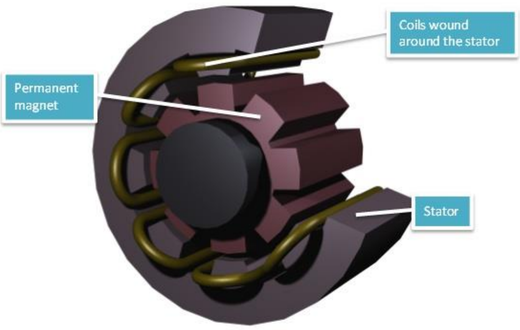

Figure 1 General components of a PM generator (Comsol, 2012).

The conductor in the stator is usually a wire that is winded many times in order to increase the *emf* or voltage generated (von Meier, 2006, pp. 93-94). The many turns of the individual conductor is arranged in a staggered design making the outgoing voltage and current curve resemble a mathematical sinusoid, as illustrated in figure 2. To further increase the efficiency of the generator it is common to use multiple conductors, usually made up by a set of three. These three conductors are not connected electronically but constitute three phases of a power circuit that correspond to the three wires, illustrated in figure 3. The phases are

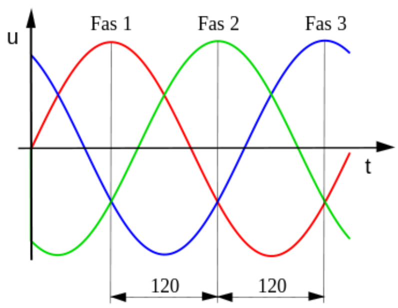

Figure 2 The emf illustrated in a graph (Wikimedia, 2015).

separated by 120^o on the stator. This three-phase system provides a smoother conversion of energy in the generator as well as other engineering advantages for power transmission.

PM generator applications

PM generators is today a part of the growing market of wind power plants and are often used in small scale power plants (with turbine rotations speeds of 150 - 500 rpm). Since the generator can operate at such low rotational speed the need for an gearbox is eliminated saving maintenance costs, weight and power losses (Kilk, 2007). As a result the PM generator is regarded as more reliable and more maintenance free in long term exploitation.

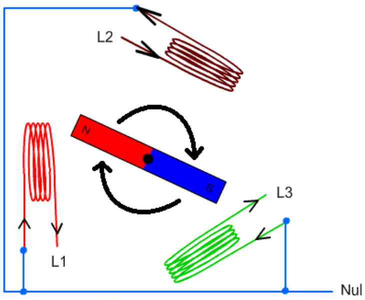

Figure 3 A schematic diagram for a three-phase system (Wikimedia, 2015).

Because of the magnets the generator does not need an external power source in order to initiate a magnetic field, which is an advantage for power plants in remote locations. However the magnets are often made of rare earth elements which make them expensive and in some applications sensitive to heat (Zipp, 2012).

Advantages and disadvantages

According to Li & Chen (2008) some general advantages of the PM generator, compared to other electrically excited generators can be summarised as:

- Reliable with low maintenance due to a limited amount of mechanical components
- No need for external power supply in order to create the magnetic field excitation
- High efficiency and energy yield
- Low weight
- High power to weight ratio

The PM generator also has some disadvantages such as:

- Difficult to handle during manufacturing, field service and repairs due to the persistent magnetic field
- High cost of magnet material
- Sensitivity to heat, causing demagnetisation of magnets

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Figure 2 Wikimedia (2015). *The emf illustrated in a graph* [Illustration]. Retrieved from: https://upload.wikimedia.org/wikipedia/commons/0/0c/3-fas-sp%C3%A4nningar.svg

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Appendix 3: Bearing Types

Bearings

Bearings are used to increase the relative movement ability of an axis when connected to other components . They keep the axis in place and also reduces the friction between the components, by that they both decrease wear on the materials and force needed to put the axis in motion (Mägi & Melkersson, 2011).

There are several different types of bearings, but on a more general level there are *rolling bearings* and *plain bearings*, illustrated in figure 1 and 2 respectively. Many of these two bearing types can withstand both thrusting and radial loads to a certain degree, but many are shaped to withstand one better than the other, or in some cases *only* one of them. Depending on which kind of load the bearing is shaped to support best you commonly talk about *thrust-* and *radial bearings* where thrust bearings support axial loads and radial bearings support radial loads.

Rolling bearings

Can be both ball bearings, using spherical bodies, and roller bearings, using cylindrical bodies. The principle of ball- and roller bearings is that the load put on the bearing is divided between the several bodies that separate the connections which minimizes friction together with its rolling movement. This however, leads to high precision demands in the manufacturing (Mägi & Melkersson, 2011).

Roller bearings are mainly created for radial loads and can carry heavier loads and work at faster speeds than ball bearings in the same size (Anonymous, 1999). The benefit with ball bearings is that while they just like roller bearings can carry radial loads they also can carry some thrust loading.

Factors that should be taken into consideration when choosing a bearing are the following:

- *Load* - The size and direction of the load are of great importance to know along with how it behaves, e.g. uniform or shocking.
- *Speed* - What speed it must manage and if it varies or is constant.
- *Life span* - The duration of how long it is in use and if it needs maintenance in the meantime.
- *Environment* - Includes aspects such as temperature, both ambient and operating, and surrounding contamination, which is a far more crucial factor than fatigue when it comes to operating failures.
- *Lubricant* - Different types of greases and oils are used depending on the bearings purpose. When grease can limit the bearings operation speed oil is more preferable to use, yet grease is more common to use due to convenience. If the amount added is too much or the viscosity of the lubricant too high then it will give the opposite effect and cause more friction. Too little lubricant or too low viscosity however, will not provide the protection needed.

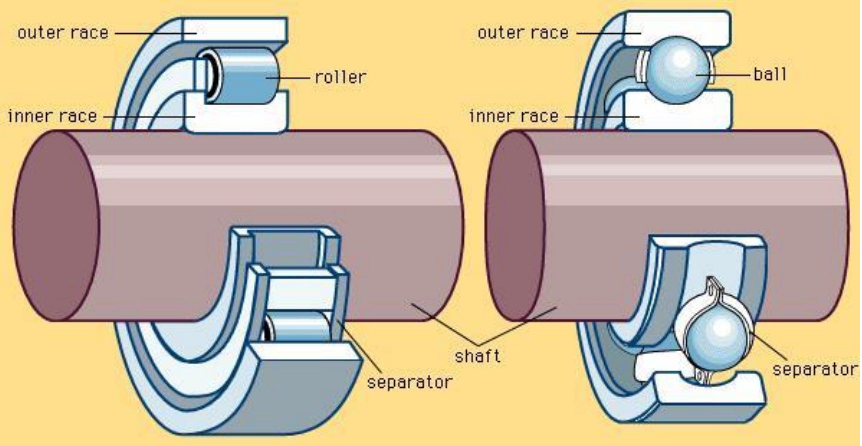

Figure 1 The image show the components of roller and ball bearings (Globalspec, 2015).

Plain bearings

This is the most common type and unlike rolling bearings this includes no moving components between the connections and instead it support the loads through sliding which makes them very dependent on the lubricant (Anonymous, 1999). And due to this reduced amount components, with no moving parts, they are generally cheaper than rolling bearings.

Figure 2 A plain bearing with no moving intermediate components (Hunger Maschinen, 2015)

The material in these can vary in a large scale with both metals and nonmetals but also compound materials. No matter which one of these is used it can overall be said that softer materials are used for light loads and high speeds while harder materials are used for the opposite (Anonymous, 1999).

Proper lubrication is essential for both of these bearing types if they are to work well.

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Appendix 4: Seals

Seals

The function of a seal is to separate pressurised fluids (either liquid or gas) from one system to another, preventing loss of fluids in an application or entry of foreign bodies into an operating medium (Brown, 1995, p. 1). Depending on requirements and operation conditions different seal types has been developed to meet the many and varying problems presented by fluid sealing. There are two main categories for seals:

- *Static seals*. The sealing takes place between two static surfaces, in other words the surfaces do not move relative to one another. They are *zero-leakage* seals, aiming at providing a complete physical barrier of a potential leakage path.
- *Dynamic seals.* In contrast to a static seal the sealing takes place between surfaces which have a relative movement. It can be a reciprocating movement of a piston in a cylinder or a rotary movement of a shaft relative to a housing.

For sealing stationary machine joints O-rings and welds are common applications. While piston rings, soft packings, moulded elastomeric rings, diaphragms and metal bushing seals are more commonly used for reciprocating movements. For sealing rotating shafts lip seals, stuffing boxes, labyrinths, spiral-groove seals and mechanical seals made out of a number of materials can be used.

Seals can generally be divided, design-wise, into two main categories depending on whether the leakage is radial between plane surfaces or axial between cylindrical surfaces. The former is termed “face seals” and it is the axial forces that control the leakage. The latter is termed a “bushing seal” where the size of the radial clearance between the shaft and the bushing controls the leakage.

Lip seals

Lips seals, see figure 1, has evolved from leather used in the 1930s to four broad categories used today. Flitney (2014, p. 106) categorise them as following:

- Elastomer lip seals used to prevent ingress or exit of liquids on rotating shafts.
- Plastic seals, usually made of PTFE (Polytetrafluoroethylene), used as an alternative to elastomer seals if fluid resistance or lack of lubrication may be a problem.
- Energy-saving or low-friction seals, can either be made of elastomer or PTFE.
- Bearing seals that usually operates at lower lip loads and which prime function is to protect bearings of contaminants.

It is important to remember that the lip is only one component of the seal. The housing in which the lip is fitted and the rotating shaft itself is equally important in order to create a tight seal which fulfil the requirements. Regarding the shaft, the most important factors are its thermal conductivity and the surface roughness and texture respectively. Lip seals are usually operating under zero or little pressure, 0.3 - 0.5 bar, in a flooded environment. An increased pressure on the lip will cause it to distortion and increase the contact area, the combination of the two will lead to increased temperatures and wear.

Basic lip seal design

The design of a lip seal looks simple but has been developed for many years by both practical experience and numerical analysis. The details of an individual design is determined by its intended application and the size of the seal (Flitney, 2014, p. 106). Figure 1 show a cross section of a traditional lip seal. In this figure the cross section of the helical spring can be seen. This spring has a torus (circumferential) shape and gives the preload pressure between the lip and the shaft.

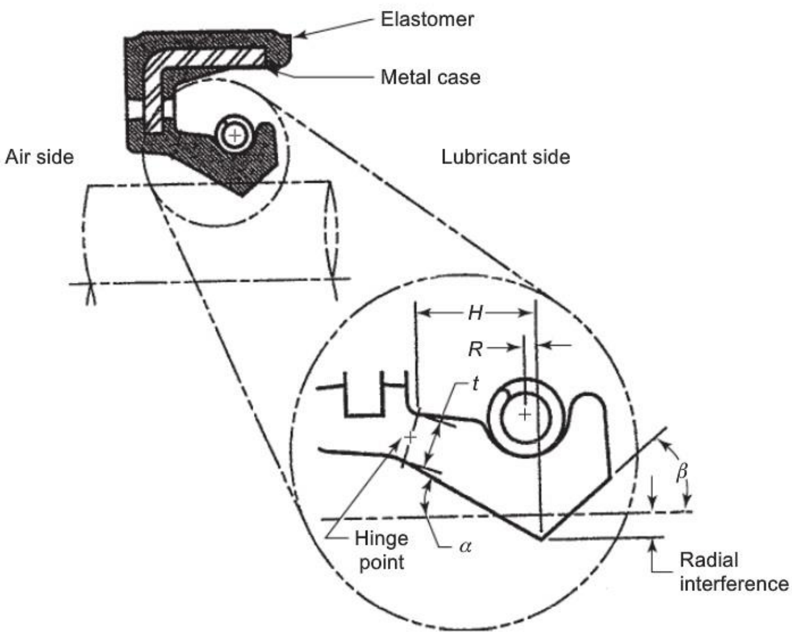


Figure 1 A cross section of a basic lip seal design (Flitney, 2014, p. 107).

Some basic geometry of the design is that the angle of the elastomer tip on the lubricant-side, $\beta = 40\text{-}45^{o}$, is usually steeper than on the air-side, $\alpha = 25\text{-}30^{o}$ (Flitney, 2014, p. 106). When the lip seal is installed and operating, these angles will change with about 10^{o}. The spring is also an important design factor. Its position is offset of the contact line of the lip a distance *R*, by typically 10% of the lip length *H*, towards the air-side of the lip. The position of the spring is important to the design because it provides the lip with the correct amount of direct loading. If the spring is positioned too close to the lubricant-side of the lips contact line leakage may occur because of tilting.

The stress profile of the seal when applied on a shaft will have a peak at the lip and then decay to zero at the edges of the contact as shown in figure 2. Because of the geometry and spring position the lip will have a more extensive contact band then on the lubricant side (Flitney, 2014, p. 110). The rotation of the shaft will cause the lip to distort since the elastomer material trying to resist the friction force, with the maximum distortion at the lip.

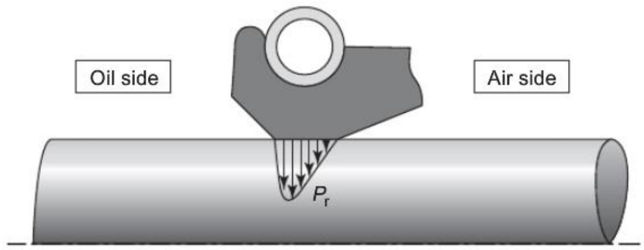


Figure 2 A illustration of how the pressure is distributed on the lip (Flitney, 2014, p. 110).

In order to prevent leakage and wear of the sealing a thin hydrodynamic oil film is needed between the shaft and the lip, the oil film also lubricates the seal (Brown, 1995, p. 141). The film is usually about 0.25 µm thick; any greater thickness could promote leakage, any less could lead to increase friction and wear. This film is illustrated in figure 3. For effective sealing it is important that the oil film is of consistent thickness and that it does not break during operation. This means that the surface finish of the lip contact area must be of high order. Any imperfections such as scratches or dents can result in local thickening and breakdown of the film which will lead to a consequent leakage of the seal. If the surface is to rough it could peak through the film and make dry contact with the lip which would result in high wear. A general recommendation of the surface finish should be of the order of 0.25 to 0.50 µm, with a surface texture that promotes retention of oil.

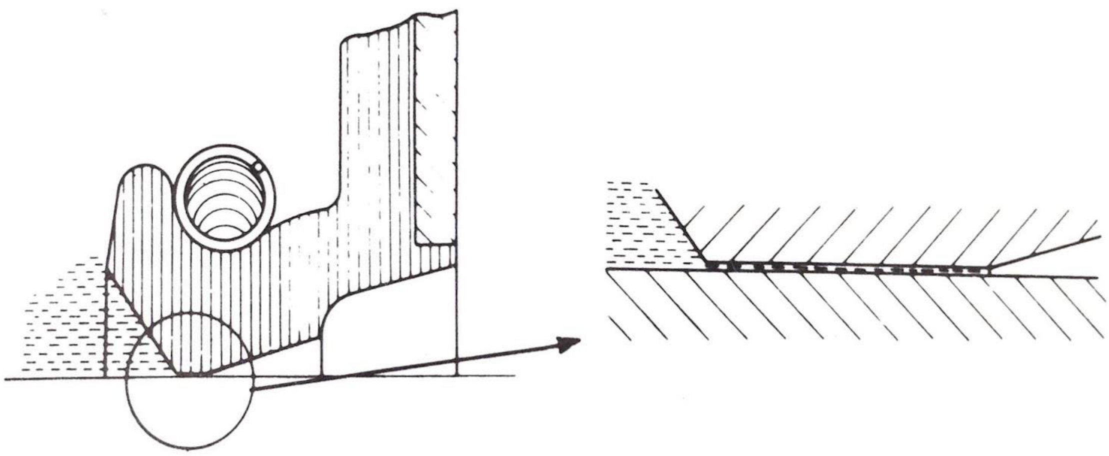
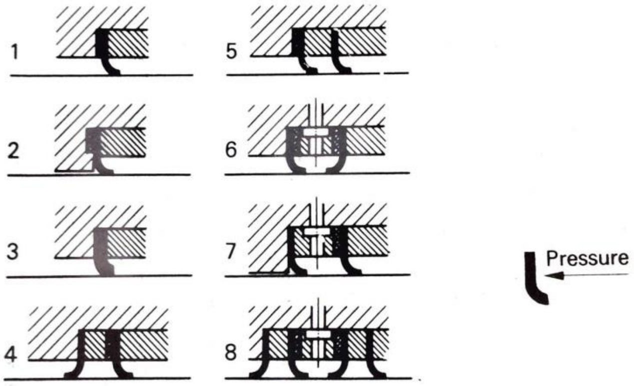


Figure 3 Oil film on a lip seal (Brown, 1995, p 141).

Grit prevention

To prevent the ingress of dirt, grit etc into the oil and the system one must design a seal application for the ambient conditions. Usually the conventional oil has a limited ability to provide such protection but it can work during certain circumstances. Otherwise one could use grease if the surrounding conditions are relatively dry (Brown, 1995, p. 150). If wet, then similar protection could be provided by using two seals mounted back to back with grease filling the space between them. Figure 4 shows a number of seal applications that can be used depending of the application and environment.



1. Pressures up to 5 bar.
2. For high pressures up to 25 bar.
3. For very low pressures, the elastomeric gasket is mounted on the pressure side and presses the seal lip like a spring against the shaft surface.
4. Double-lips for pressure and vacuum service.
5. Double-lips for abrasive service.
6. Arrangement for flushing, heating, cooling, lubrication and quenching.
7. Arrangement for pressure and vacuum and possibility for flushing, heating, cooling, lubrication and quenching.

Figure 4 Grit preventing lip seals applications. (Brown, 1995, p 150)

Separating two fluids

Two fluids can be separated by using two lip seals mounted back to back, see figure 5, (Müller & Nau, 1998). The chamber between the seals can either be vented and drained if filled or filled with a compatible grease which could also increase the lifespan of the seal.

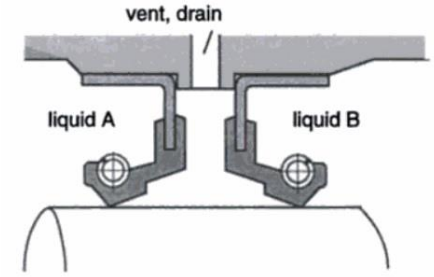


Figure 5 Illustration of how to separate two fluids (Müller & Nau, 1998).

Stern-tube seals

Lip seals are specifically used in stern tubes, which is a complete system widely used in ships to carry the tail shaft, lubricate it, seal it from outer contamination, connect it with the propeller and provide bearings.

O-rings

The O-rings *are* possible to use for sealing rotating shafts, although it is not as common to use as lip seals. It is limited to low speeds though.

Positive-lubrication rotary seals

Unlike the ordinary lip seal this has two completely different sides. One outer which is flat and keeps all the contamination out and one inner which is shaped in a way that promotes lubrication when the shaft is in movement, see figure 6 (Flitney, 2014, p. 157-161).

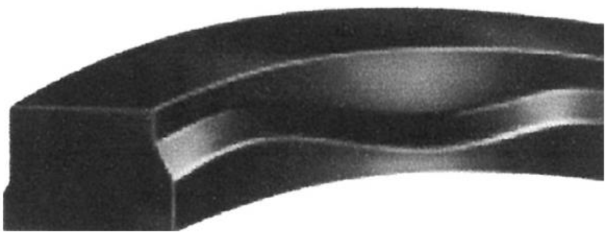


Figure 6 Shape of a positive-lubrication seal (Flitney, 2014, p. 158)

The waves pumps lubrication into the seal contact surface and makes the shaft to spin more easily and with less resistance and enables the seal to work at higher speeds compared to other polymeric seals. This however, cannot be performed without some leakage, but in some systems that can be tolerated.

Mechanical seals

This is nowadays one of the primary methods to seal shafts in rotary machines using two flat radial faces where one of them is fixed while the other rotates with the shaft (Flitney, 2014, p. 162-163). There are various combinations in how these look depending on different uses, pressures and environments. In figure 7 the main parts of a mechanical seal are described.

Overall it can be said that there are three different types:

- Elastomer-bellows seals
- Pusher seals
- Metal-bellows seals

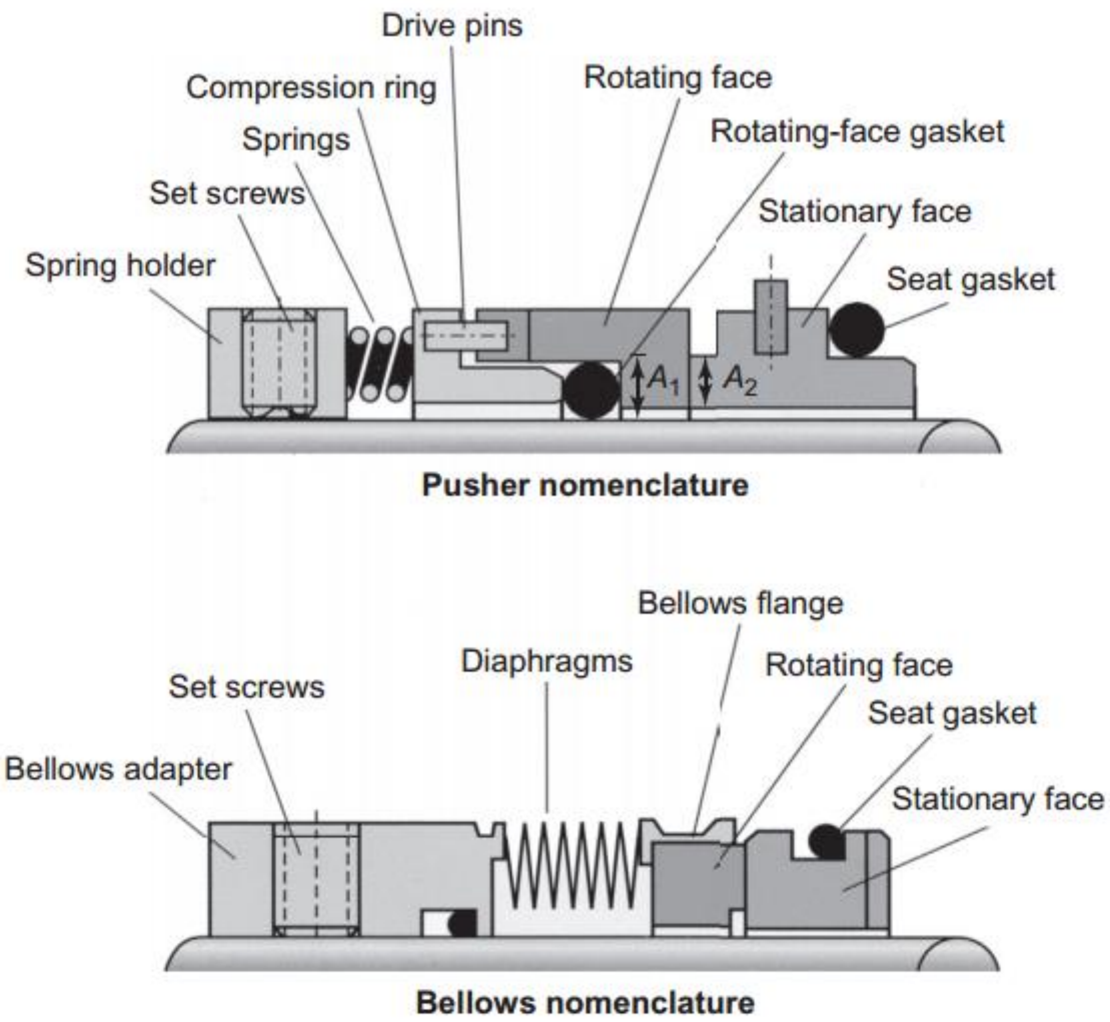


Figure 7 Schematic description of different mechanical sealing types (Flitney, 2014, p. 163).

As is shown in figure 7 pusher seals consists of one stationary seal face fitted in a flange and one rotating seal face which also can move in axial direction and is kept in place by one or more springs connected either to a shaft sleeve or directly in the shaft (Flitney, 2014, p. 163). The stationary seal face is often made of a material that is worn down because of the friction against the rotating face and replaced during maintenance. In addition there is also a 'dynamic secondary seal', often in shape of an O-ring made of elastomer or PTFE, which is connected to the rotating face and can move in the same directions.

The bellows seals are in general very similar in the concept of how they work. The big difference is that they use metal bellows to gain flexibility in the design and by that no dynamic secondary seal' is necessary and instead a static one can be used. This simplifies the choice of material.

Clearance seals
The clearance seals are widely used when sealing rotating shafts. Although they do not provide complete isolation, which makes some leakage inevitable, there are some advantages with this type (Flitney, 2014, p. 243).

- Very low friction compared to others
- They can operate in high speeds
- Minimal wear, particularly when operating in gas at high speed
- Able to handle contamination without increasing wear on the material

Labyrinth seals
A labyrinth seal is a type of seal that prevents leakage by providing a tortuous path (Brown, 1995, p 411). The sealing efficiency then depends on the gap, the length and the form of the path, examples are illustrated in figure 8. A smaller gap, given that contact can be avoided during operation, is better for the seals ability to prevent leakage. Also, tapered teeth and altering teeth or serrations is generally considered to reduce the leakage as well.

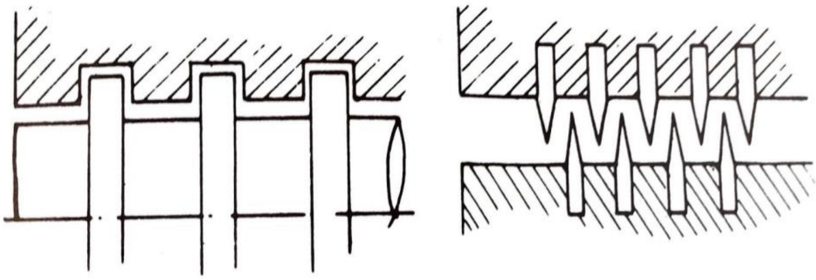


Figure 8 Illustrated examples of labyrinth seals (Brown, 1995)

Segmented seals
A segmented seal is a type of circumferential seal which is widely used in water turbines applications (Flitney, 2014, p. 270-273). They do not allow the same amount of leakage as labyrinth seals although they can not compete with mechanical seals when it comes to leakage nor pressure. The advantages they do have compared to mechanical seals however, are that they are relatively compact and have no moving

Figure 9 Example of a segmented seal (Flitney, 2014, p. 271)

parts except for the shaft sleeve. These qualities are of course very important when trying to reduce the space usage in a machine but there is one major problem that can be encountered in these situations: if the seals are to withstand higher pressures it might be necessary to place a series of seals, which will occupy more space. Carbon is a common material to use in this type of seal.

Bibliography

Brown, M. (1995). *Seals and sealing handbook.* Oxford: Elsevier Science.

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Müller, H. K., & Nau, B. S. (1998). *Fluid sealing technology: principles and applications.* New York: Dekker.

Figure references

Figure 1: Flitney (2014, p. 107). *A cross section of a basic lip seal design* [Illustration].

Figure 2: Flitney (2014, p. 110*). A illustration of how the pressure is distributed on the lip* [Illustration].

Figure 3: Brown (1995, p 141). *Oil film on a lip seal* [Illustration].

Figure 4: Brown (1995, p 150). *Grit preventing lip seals applications* [Illustration].

Figure 5: Müller & Nau (1998). *Illustration of how to separate two fluids* [Illustration].

Figure 6: Flitney (2014, p. 158) *Shape of a positive-lubrication seal* [Illustration].

Figure 7: Flitney (2014, p. 163) *Schematic description of different mechanical sealing types* [Illustrator].

Figure 8: Brown (1995). *Illustrated examples of labyrinth seals* [Illustration].

Figure 9: Flitney (2014, p. 271) *Example of a segmented seal* [Illustration].

Appendix 5: Corrosion Types

Pitting

Causes small holes randomly located across the material. Common in areas with stagnant fluids (Davis, 2014, p. 102-107). The appearance of these holes can vary both in size and how they are placed across a surface, see figure 1 and 2. Mostly they are relatively small but can be easy to see if they are placed on a smooth surface. If they however are placed on a corroded and rough surface they are more camouflaged and hard to discover. This is a big problem since a very small defect like this can cause great damage depending on its location.

Figure 1 Schematic illustration of pitting corrosion (Davis, 2014).

Figure 2 Pitting corrosion on metal (Davis, 2014).

Erosion-corrosion

Erosion and corrosion at the same time caused by fluids with high velocity and turbulent flow (NyTeknik, 2015). Almost anything that is exposed to flowing water can be a victim to this, such as pipes, pumps and turbine blades. Unlike the other this type of corrosion does not cause the typical orangish corrosion colour but instead leaves bright pits, sometimes in shape of a horseshoe, see figure 3. This makes it much less resistant to wearing and vibration.

Metals that are dependent of thick layers of external corrosion protection are rather easily affected by erosion-corrosion due to its lack of attachment to the metal. The natural protective coating that some metals possess are necessary to withstand this type of attack. Stainless steel and especially titanium are examples of these and are as good as immune in most environments (Davis, 2014, p. 134-140)

Figure 3 Schematic illustration of erosion corrosion (Davis, 2014).

Dealloying corrosion
Selective corrosion of a specific material in alloys (Davis, 2014, p.158). Example of this is de-zincification, where the zinc in brass corrodes and only deteriorated copper is left behind, and graphitic corrosion, where cast iron loses its iron and instead becomes a brittle piece of graphite, see figure 4.

Figure 4 Schematic illustration of dealloying corrosion (Davis, 2014).

Intergranular corrosion
An attack on the grain boundaries of a metal, see figure 5 (Nationalencyklopedin, 2015). Often caused due to impurities in the metal but the actual mechanism can vary depending on the alloy system.

Figure 5 Schematic illustration of intergranular corrosion (Davis, 2014).

Bibliography

Davis, J. (2014). *Corrosion - Understanding the Basics.* Retrieved 05 18, 2015, from http://app.knovel.com/web/toc.v/cid:kpCUB00002/viewerType:toc/root_slug:corrosion-understanding/url_slug:kt00C5UOJ1

Figure references

Figure 1: Davis (2014). *Schematic illustration of pitting corrosion* [Illustration].

Figure 2: Davis (2014). *Pitting corrosion on metal* [Illustration].

Figure 3: Davis (2014). *Schematic illustration of erosion corrosion* [Illustration].

Figure 4: Davis (2014). *Schematic illustration of dealloying corrosion* [Illustration].

Figure 5: Davis (2014). *Schematic illustration of intergranular corrosion* [Illustration].

Appendix 6: Extract from Lesjöfors' Spring Catalogue

The following is an extract from Lesjöfors spring catalog SS 2387-2 describing the characteristics of the chosen concept spring no.2931.

COMPRESSION SPRINGS

SS 2387-2 Swedish Standard

D_t	D_m	L_o	n_v	F_n	L_n	s_n	c	Cat. no.
0,8	4	6	3,5	29,59	4,41	1,59	18,6	2889
0,8	4	8,73	5,5	29,59	6,23	2,5	11,8	2890
0,8	4	12,8	8,5	29,59	8,96	3,86	7,66	2891
0,8	4	18,3	12,5	29,59	12,6	5,68	5,21	2892
0,8	4	26,5	18,5	29,59	18,1	8,4	3,52	2893
0,8	5	7,24	3,5	26,33	4,48	2,76	9,53	2894
0,8	5	10,7	5,5	26,33	6,34	4,34	6,06	2895
0,8	5	15,8	8,5	26,33	9,12	6,71	3,92	2778
0,8	5	22,7	12,5	26,33	12,8	9,87	2,67	2897
0,8	5	33	18,5	26,33	18,4	14,6	1,8	2898
0,8	6,3	9,28	3,5	22,28	4,6	4,68	4,76	2899
0,8	6,3	13,9	5,5	22,28	6,53	7,35	3,03	2900
0,8	6,3	20,8	8,5	22,28	9,43	11,4	1,96	2901
0,8	6,3	30	12,5	22,28	13,3	16,7	1,33	2902
0,8	6,3	43,8	18,5	22,28	19,1	24,7	0,901	2903
0,8	8	12,6	3,5	18,17	4,79	7,81	2,33	2904
0,8	8	19,1	5,5	18,17	6,83	12,3	1,48	2905
0,8	8	28,9	8,5	18,17	9,89	19	0,958	2906
0,8	8	41,9	12,5	18,17	14	27,9	0,651	2907
0,8	8	61,4	18,5	18,17	20,1	41,3	0,44	2908
0,8	10	17,6	3,5	14,91	5,06	12,5	1,19	2909
0,8	10	26,9	5,5	14,91	7,25	19,7	0,758	2910
0,8	10	40,9	8,5	14,91	10,5	30,4	0,49	2911
0,8	10	59,6	12,5	14,91	14,9	44,7	0,333	2912
0,8	10	87,7	18,5	14,91	21,5	66,2	0,225	2913
1	5	7,44	3,5	44,79	5,51	1,93	2,3	2914
1	5	10,8	5,5	44,79	7,79	3,03	1,48	2915
1	5	15,9	8,5	44,79	11,2	4,68	9,58	2916
1	5	22,6	12,5	44,79	15,7	6,88	6,51	2917
1	5	32,8	18,5	44,79	22,6	10,2	4,4	2918
1	6,3	9,02	3,5	39,72	5,6	3,42	11,6	2919
1	6,3	13,3	5,5	39,72	7,93	5,37	7,4	2920
1	6,3	19,7	8,5	39,72	11,4	8,3	4,79	2921
1	6,3	28,3	12,5	39,72	16,1	12,2	3,26	2922
1	6,3	41,1	18,5	39,72	23,1	18,1	2,20	2923
1	8	11,7	3,5	33,47	5,77	5,89	5,68	4812
1	8	17,4	5,5	33,47	8,19	9,26	3,61	2925
1	8	26,1	8,5	33,47	11,8	14,3	2,34	2926
1	8	37,7	12,5	33,47	16,7	21	1,59	2927
1	8	55,1	18,5	33,47	23	31,1	1,07	2928
1	10	15,5	3,5	27,65	5,99	9,51	2,91	2929
1	10	23,5	5,5	27,65	8,54	14,9	1,85	2930
1	10	35,5	8,5	27,65	12,4	23,1	1,2	2931
1	10	51,4	12,5	27,65	17,5	34	0,814	2932
1	10	75,4	18,5	27,65	25,1	50,3	0,550	2933
1	12,5	21,6	3,5	22,69	6,33	15,2	1,49	2934
1	12,5	33	5,5	22,69	9,07	24	0,947	2935
1	12,5	50,2	8,5	22,69	13,2	37	0,613	2936
1	12,5	73,1	12,5	22,69	18,7	54,4	0,417	2937
1	12,5	107	18,5	22,69	26,9	80,6	0,282	2938

D_t	D_m	L_o	n_v	F_n	L_n	s_n	c	Cat. no.
1,25	6,3	9,28	3,5	67,85	6,89	2,39	28,4	2939
1,25	6,3	13,5	5,5	67,85	9,74	3,75	18,1	2940
1,25	6,3	19,8	8,5	67,85	14	5,8	11,7	2941
1,25	6,3	28,2	12,5	67,85	19,7	8,53	7,95	2942
1,25	6,3	40,9	18,5	67,85	28,2	12,6	5,37	2943
1,25	8	11,3	3,5	59,85	7,01	4,32	13,9	2944
1,25	8	16,7	5,5	59,85	9,93	6,78	8,82	2945
1,25	8	24,8	8,5	59,85	14,3	10,5	5,71	2946
1,25	8	35,5	12,5	59,85	20,1	15,4	3,88	2947
1,25	8	51,7	18,5	59,85	28,9	22,8	2,62	2948
1,25	10	14,4	3,5	51,11	7,21	7,2	7,1	2949
1,25	10	21,5	5,5	51,11	10,2	11,3	4,52	2950
1,25	10	32,3	8,5	51,11	14,8	17,5	2,92	2951
1,25	10	46,5	12,5	51,11	20,8	25,7	1,99	2952
1,25	10	67,9	18,5	51,11	29,9	38,1	1,34	2953
1,25	12,5	19,1	3,5	42,23	7,49	11,6	3,64	1627
1,25	12,5	28,9	5,5	42,23	10,7	18,3	2,31	4997
1,25	12,5	43,7	8,5	42,23	15,5	28,2	1,5	1445
1,25	12,5	63,3	12,5	42,23	21,8	41,5	1,02	1424
1,25	12,5	92,8	18,5	42,23	31,4	61,4	0,688	1360
1,25	16	27,5	3,5	33,93	7,96	19,6	1,73	2954
1,25	16	42,2	5,5	33,93	11,4	30,8	1,1	2955
1,25	16	64,1	8,5	33,93	16,6	47,5	0,714	2956
1,25	16	93,4	12,5	33,93	23,5	69,9	0,485	2957
1,25	16	137	18,5	33,93	33,9	103	0,328	2958
1,6	8	11,7	3,5	107,1	8,82	2,88	37,2	2959
1,6	8	17	5,5	107,1	12,5	4,52	23,7	2960
1,6	8	24,9	8,5	107,1	17,9	6,99	15,3	2961
1,6	8	35,5	12,5	107,1	25,2	10,3	10,4	2962
1,6	8	51,3	18,5	107,1	36,1	15,2	7,04	2963
1,6	10	14	3,5	95,85	8,95	5,03	19,1	2964
1,6	10	20,6	5,5	95,85	12,7	7,9	12,1	4998
1,6	10	30,5	8,5	95,85	18,2	12,2	7,85	2966
1,6	10	43,6	12,5	95,85	25,7	18	5,34	2967
1,6	10	63,4	18,5	95,85	36,8	26,6	3,61	2968
1,6	12,5	17,6	3,5	82,47	9,2	8,45	9,76	2969
1,6	12,5	26,3	5,5	82,47	13,1	13,3	6,21	2970
1,6	12,5	39,4	8,5	82,47	18,8	20,5	4,02	2971
1,6	12,5	56,7	12,5	82,47	26,5	30,2	2,73	2972
1,6	12,5	82,8	18,5	82,47	38,1	44,7	1,85	2973
1,6	16	24	3,5	66,95	9,59	14,4	4,65	2974
1,6	16	36,3	5,5	66,95	13,7	22,6	2,96	2975
1,6	16	54,7	8,5	66,95	19,8	34,9	1,92	2976
1,6	16	79,3	12,5	66,95	27,9	51,4	1,3	2977
1,6	16	116	18,5	66,95	40,2	76,1	0,88	2978
1,6	20	33,2	3,5	54,94	10,1	23,1	2,38	2979
1,6	20	50,8	5,5	54,94	14,5	36,2	1,52	4999
1,6	20	77,1	8,5	54,94	21,1	56	0,981	5000
1,6	20	112	12,5	54,94	29,9	82,4	0,667	2982
1,6	20	165	18,5	54,94	43	122	0,451	2983

Retrieved from: http://catalog.lesjoforsab.com/pdf/en/chapters/29-33_EN.pdf

Appendix 7: Spring Calculations

The following describes the spring calculations more specifically.

The following calculations is based on spring: Lesjöfors' SS 2387 1x10x35.5 cat.no. 2931, found in appendix 6, and has the following characteristics:

D_t = 1 mm (Wire diameter)
D_m = 10 mm (Mean spring diameter)
L_0 = 35.5 mm (Unloaded length)
L_n = 12.4 mm (Minimum working length)
c = 1.2 N/mm (Spring rate)

The data for number of parallel springs n and the area A of the pressure plate is as following:

n = 6
A = 0.005 m^2

The spring will be compressed by 5.5 mm when mounted in the casing and by 23 mm when the bladder is completely filled. This is the spring's deformation and is listed below.

δ_1 = 5.5 mm
δ_2 = 23 mm

The spring rate c is defined as:

Equation 6.1 Definition of spring rate, c, by force, F, and deformation, δ, (Mägi & Melkersson, 2011, p. 130)

$$c = \frac{F}{\delta}$$

The total force F of n parallel springs is defined as:

Equation 6.2 Total force of n parallel springs (Mägi & Melkersson, 2011, p. 133)

$$F = \sum_{i=1}^{n} F_i = \sum_{i=1}^{n} c_i \delta = \delta \sum_{i=1}^{n} c_i$$

Assuming that the oil pressure is equal to the pressure acting on the pressure plate caused by the applied spring force. The pressure p_{spring} is then equal to the quotient of the force F divided by the area A of the pressure plate as defined in equation 3.3:

Equation 6.3 Pressure, P, in relation to force, F, and area, A, (Çengel, Turner, & Cimbala, 2008, p. 39)

$$p_{spring} = \frac{F}{A}$$

The resulting p_{spring} is thereby equal to Δp (the overpressure of the system).

By using equation 3.1, 3.2 and 3.3 the following data could be calculated:

$$F_1 = \sum_{i=1}^{n} F_i = \sum_{i=1}^{n} c_i \delta = \delta \sum_{i=1}^{n} c_i = 5.5 * 6 * 1.2 = 62.6 \text{ N}$$

$$F_2 = \sum_{i=1}^{n} F_i = \sum_{i=1}^{n} c_i\delta = \delta \sum_{i=1}^{n} c_i = 23 * 6 * 1.2 = 165.6 \text{ N}$$

$$p_1 = \frac{F_1}{A} = \frac{62.6}{0.005} = 12520 \text{ Pa} = 0.125 \text{ bar}$$

$$p_2 = \frac{F_2}{A} = \frac{165.6}{0.005} = 33120 \text{ Pa} = 0.331 \text{ bar}$$

References

Mägi, M., & Melkersson, K. (2011). *Lärobok i maskinelement del A.* Gothenburg: EcoDev International AB.

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