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Bearings in Wave Energy Converters

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Bearings in wave energy converters

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Abstract

Wave energy and wave energy converters is a fast rapidly developing field of research and energy harvesting. In recent years, more and more designs have seen operational success, and more and more are in development. Wave energy converters face a challenge not properly explored until recently, high loaded, oscillating motion in a highly hostile environment. Which poses a multitude of challenges ranging from contact fatigue to corrosion wear. However, this field is still in early development, seeing little to no research published about it. This work intends to inform about the challenges these wave energy designs pose in tribology and more specifically to bearings, through a literature study and review. The review establishes a rating for different bearing designs based on how applicable a certain bearing selection would be based on available research. Reaching the conclusion that whilst currently inappropriate to employ, seawater lubricated bearings could reach commercial viability in the future for wave energy devices. Additionally, with the help of excellent sealing solutions and well conducted lubrication regimes, both sliding bearings and rolling element bearings have their advantages and disadvantages and can make use of a multitude of different materials.

Keywords: Wave energy converter, bearings, tribology

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Sammanfattning

Vågkraft och vågkraftsgeneratorer är ett område som växer snabbt i intresse för både forskning och produktutveckling. På senare år har fler och fler vågkraftsgeneratorer och designer för dessa sett framgång i prototyptester och flera är på fortsatt utveckling. Vågkraftsgeneratorer står inför flera utmaningar, med de sammansatta faktorerna av en väldigt korrosiv miljö, höga krafter och oscillerande rörelse. Vilket stället flera krav på designers på allt ifrån korrosionsskydd till materialkunskap krig utmattning av maskinkomponenter. Dessvärre finns ytterst lite noga dokumenterad forskning kring området då det är en väldigt ung bransch. Denna rapport söker att utforska och informera kring de utmaningar som kan ställas på vågkraftsgeneratorer inom specifikt tribologi och specifikt för lager och lagerval. Arbetet fokuserar på en litteraturstudie över de möjliga utmaningarna området skapar. Grundat på relevant forskning inom liknande områden betygsattes ett urval av lagerval för vågkraftsgeneratorer. Där slutsatserna pekar på att då det möjligtvis är olämpligt i nuvarande läge att nytta saltvatten som smörjningsmedel, i framtiden kan detta bli en kommersiell verklighet. Där både glidlager och rullningslager har sina fördelar och nackdelar inom applikationen, med noga valda materialkombinationer, smörjningsmedel och tätningar.

Nyckelord: Vågkraftsgenerator, lager, tribologi

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1. Introduction

Wave energy converters (WEC's) are currently seeing more relevance and research due to the growing importance of renewable and sustainable energy sources. However, the technology and industry standard for mechanical parts in these devices (WEC's) are not as well developed as its counterpart in wind power.

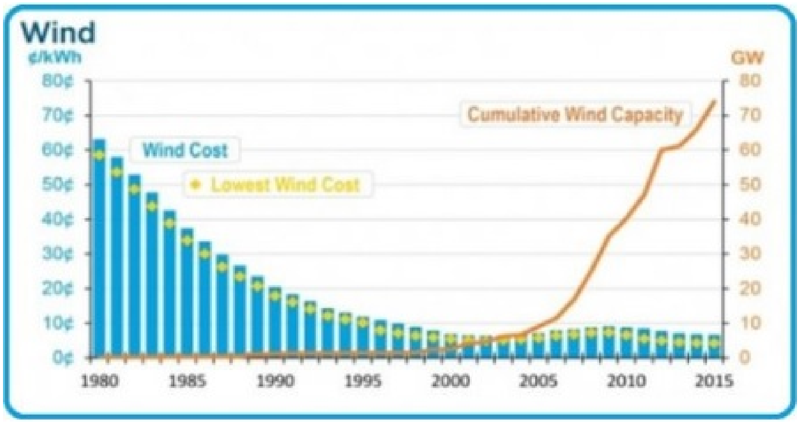

Figure 1.1: The cost of energy in comparison to the growth of wind energy [1].

More specifically, the tribological aspects in WEC's is in need of further research to establish a higher technical readiness level. One vital factor in this area are bearings, where both lubrication and wear rates represent a new challenge when in a hostile environment [11]. Where the definition of "hostile environment" in this sense is regarded as a (if not the most) hostile environment to material [2]. Not only due to corrosion from the saltwater, but also because of organic matter such as algae, which can cause severe corrosion with time. Furthermore, the nature of the motion in WEC's is oscillating because of the up and down motion of the waves, causing yet another issue when designing WEC's as most design approaches assumed a fully rotational motion.

Another challenge is the aspect of scale in these devices, where certain conditions would apply for a smaller test model, a full-scale model would impose new issues that would not arise in a smaller model [3]. Which presents a challenge to what kind of bearings would be suitable, since geometry plays a big role in what kind of bearings are applicable, and subsequently their lubrication. Surprisingly (or justifiably not), bearing manufacturers seem to claim their own solution to be the most suitable for bearings in WEC's [12,13], ranging from polymer bearings to ceramic/steel bearings. Unfortunately, the reasoning as to why is often left out, most probably due to internal research not being released publicly.

Bearings in WEC's is of particular interest where the harsh conditions create a need to fully understand the different issues that could arise. To that end, a thorough investigation of the matter of tribology could lead to significant financial savings [14].

1.1 Scope

The scope of the thesis is to document different bearing selections for a WEC technology, the point absorber and their challenges within the field of tribology as a literature review. These challenges are mainly (but not limited to) wear, lubrication and expected life for the bearings inside the WEC's. A special focus is put on the Noviocean designs. Additionally, different available and usable bearing selections will be investigated for use in WEC's. The review is intended to provide a pre-study/literature review for further investigations in a longer project concerning tribological aspects in WEC designs.

1.2 Goals and research questions

This thesis seeks to develop a further understanding of the tribological aspects of bearing and lubrication aspects within different WEC designs with their respective advantages and drawbacks. The research question(s) to complement the goals are the following:

- Why does the choice of lubrication impact the reliability of bearings in WEC designs?
- Why does scalability impact the choice of bearings in WEC's?
- Why does different bearing materials impact the potential reliability of WEC's?

1.3 Delimitations

The main delimitation of this project include:

- No detailed force analysis, estimations and extrapolated experimental data will be used instead.
- No experimental testing.
- No detailed material design approach will be taken.

1.4 Methodology

The methodology of the thesis consisted of an evaluation of different bearings by how effectively they complement different WEC technologies with a focus on point absorber WEC technology. A flowchart of the thesis is shown in figure 1.2 below to illustrate the work process.

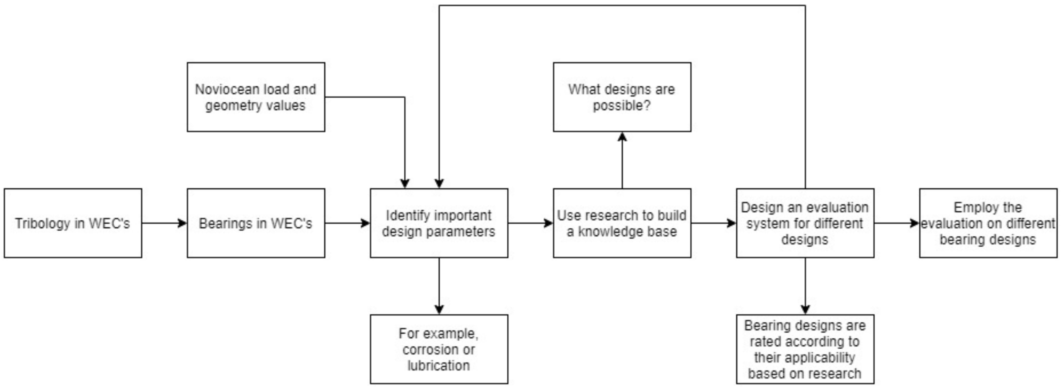

Figure 1.2: Flowchart of the workprocess for the report.

Bearing designs were compared to each other based on some tribological aspects in relation to how applicable they are to WEC technology. Where different bearing designs have better or worse attributes based on current research into tribological behaviors of WEC designs. The evaluation consists of the following aspects:

- Reliability
  - Loads
  - Wear
  - Corrosion
- Scalability
- Maintenance
  - Lubrication
  - Cleaning

Where each of the sections and subsections were evaluated using a rating system (0-1) for how applicable each bearing selection would or could be, supported by current research into each of the aspects. After which the data was organised into box plots for each bearing selection in order to see a potential range for each design. Furthermore, in parallel to the evaluation, a survey were issued among industry professionals and university professors (all in fields concerning tribology/contact mechanics) to investigate possible solutions to bearings in WEC's based on certain conditions. Where the goal was to offer an amount of validation of the literature review and evaluation result, as the survey can reflect the prevalent issues and complexity in the provided harsh conditions. Additionally, the reviewed research offered varied analyses of different lubrication regimes, where some included saltwater/seawater, some made use of distilled water or similar. The effect of this means some evaluated bearing choices are rated with the use of distilled water instead of saltwater.

2. State of the art

The application of bearings in wave energy converters are dependent on the type of converters used, what kind of lubrication is possible/should be used and the available (suitable) bearing technology for the different WEC's. Following is the necessary baseline information needed to make an assessment on bearing application.

2.1 Wave Energy Converters

The technology of wave energy converters is an old design, dating back more than 200 years [2]. However, only in recent years has it seen a rise in interest due to the growing need for sustainable energy harvesting. As such, there are plenty of different WEC designs that can fulfil this need. In order to extract the maximum amount of energy, WEC's are usually restricted to a 1-DOF (1 degree of freedom), sometimes 2-DOF system, by common notation, these directions are given below, see figure 2.1.

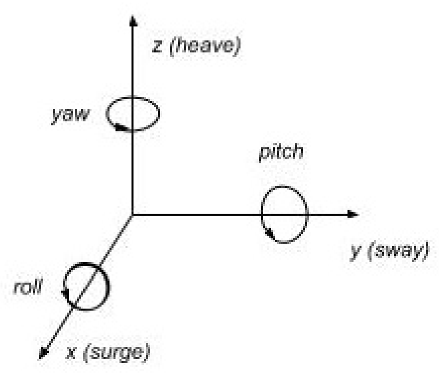

Figure 2.1: Coordinate system describing motion of WEC's.

Two common concepts in WEC technology are attenuator and terminator. Where an attenuator is a type of WEC that absorbs energy parallel to the incident wave direction. Whereas a terminator absorbs energy perpendicular to the direction of the wave. Since power generation require a good efficiency to be comparable to other systems (wind power, wave power etc), it is important that the WEC is designed in such a way that as much energy as possible is absorbed by the generators. And as little energy as possible is lost by misalignment of the PTO (Power Take-Off) unit. A symmetric WEC would to an extent help with this issue as well.

2.1.1 Point/line absorber

The most commonly (and perhaps easiest) application of a WEC is the point absorber see figure 2.2. This type of WEC absorbs energy in pitching or heaving motion generated by the wave action. After which, the motion is converted to energy with the help of the PTO (power take-off unit). Additionally, instead of a heave plate on a circular point, a longer "line" could be used instead, coining the term line absorber.

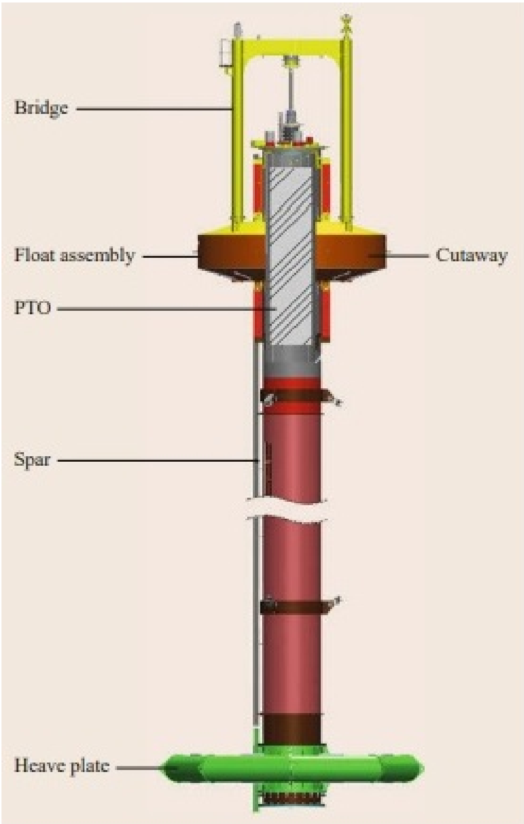

Figure 2.2: Point absorber concept from Ocean Power technologies [2].

2.1.2 Overtopping device

The type of WEC known as an overtopping device capture the incident water from waves, storing the water inside a reservoir above sea level. Leading the water through a turbine and subsequently back into the sea. An example of an overtopping device is the Wave Dragon design, see figure 2.3

Figure 2.3: 1:4.5 scale test of Wave Dragon design (overtopping device) [3].

2.1.3 Oscillating water column

An oscillating water column employs the idea of the change in pressure due to airflow when ocean waves cause a rise and sink in a "water column", see figure 2.4.

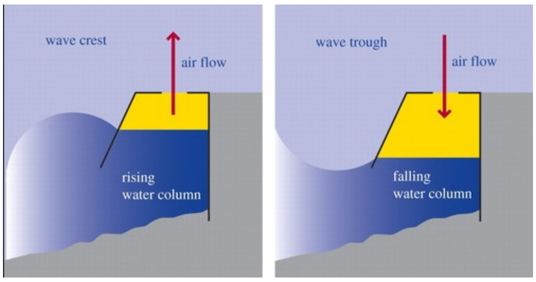

Figure 2.4: Simplified schematic design for OWC device [4].

Since the motion of the wave will cause an oscillating motion, special types of wind turbines are needed to accommodate the oscillation for the PTO. Such types of wind turbines are the Wells turbine, Impulse turbine and Dennis-Auld turbine. These types of turbines are called self-rectifying turbines and enable turbine rotation regardless of the direction of air flow. While some OWC applications have been decommissioned (e.g. Pico plant in Portugal), some are currently operating. One of them being the Mutriku power plant in Spain, by Wavegen, see figure 2.5 below.

Figure 2.5: Mutriku OWC wave power plant in Spain by Wavegen [3].

2.1.4 Submerged pressure differential device

The submerged pressure differential device is a type of converter akin to the OWC (but submerged). This type of device uses an air filled chamber as the pressure differential system. The core concept for this device is very similar to the OWC as it utilizes the same induced pressure difference from a trough and a crest as the device heaves. Since the dynamic pressure in the air chamber changes as the device follows a crest or trough of a wave. An example of this type of device is the AWS (Archimedes Wave Swing), see figure 2.6. Although this type of device is less explored compared to other WEC technologies, it has potential since the construction is relatively simple. However, submerging the entire WEC underwater presents other challenges such as sealant.

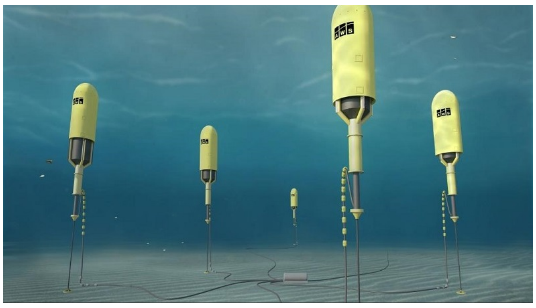

Figure 2.6: Representation of submerged pressure differential device by AWS [5].

2.1.5 Oscillating wave surge converter

A wave surge converter is usually based on the idea of a body that utilizes the surge motion of a wave (in the direction of the wave, see figure 2.7) to capture the energy. As the horizontal velocity of the wave crosses the buoy, the body absorbs the energy through the motion. Current constructions that utilize this technology is either with a flap or a piston, that can efficiently absorbs the energy.

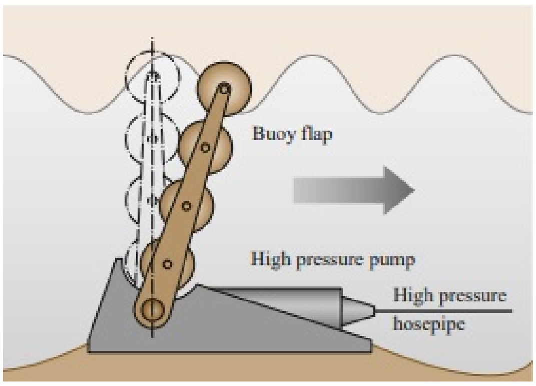

Figure 2.7: Working principle of the Oyster OWSC device [2].

2.2 Bearings

Bearings are a critical part for any design that requires the enabling of relative motion. Furthermore, proper bearing design and selection can result in lower wear, lower friction and lower cost for any product utilizing bearings [6, 14]. They come in many different varieties and manufactured by many different companies. To that end, the possible types of bearings intended for WEC technology is effectively zero. Where the wave energy sector is not established enough to the point where bearing manufacturers would be notably interested in the market. Although there exists bearings that are said to be fully capable of complete immersion in saltwater with sustainable life [13]. These types of bearings would contradict previous research of the area where full immersion in saltwater (with organic matter as well) would be hugely detrimental to both wear and friction. The relevant bearings can be divided into two categories, rolling element bearings and journal bearings. Where journal (plain) bearings is counted in the fluid film bearing category, even though some journal bearings do not require/are not designed for fluid film lubrication. For some WEC devices, certain bearing designs would be more easily applied to the given device, for instance, the submerged WEC variants (OWSC, AWS) operate while immersed in seawater. Meanwhile, the OWC design utilizes the air flow produces by the incident waves, rather than the water itself. For the case of this report, the point absorber/line absorber work in both environments, being semi-submerged. Which potentially means that a couple of different designs/selections could work for different spots in the WEC.

2.2.1 Rolling element bearings

Rolling element bearings are bearings which carry load with rolling elements e.g balls between two races, the outer and inner ring, see figure 2.8. These elements take on many different geometrical shapes, coining the different roller bearing types:

- Cylindrical roller bearing
- Tapered roller bearing
- Spherical roller bearing
- Needle roller bearing
- Ball bearing

The names of these bearings adhere to the type of geometrical shape they have. Naturally, these types of rolling elements exist in plenty of different types of bearing applications. An example of this is the cylindrical roller bearing which can be used in many different ways. Such as the mounting of additional rows or as well as using a radial or axial bearing.

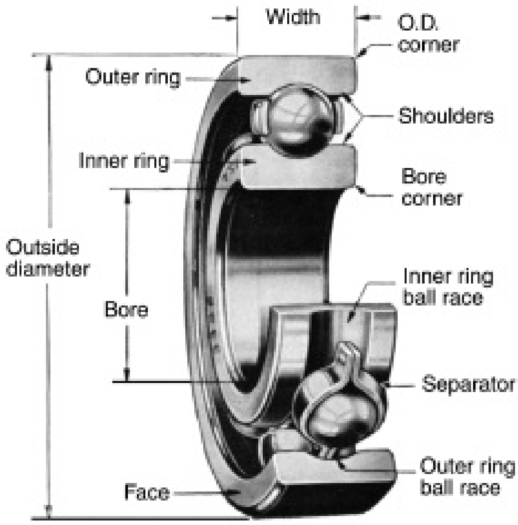

Figure 2.8: Nomenclature and design of a Ball bearing [6].

2.2.2 Fluid-film bearings

Fluid film bearings, as the name indicates it related to the use of a thin fluid film in the bearing contact, between the rotating element and its raceway, see figure 2.9 below. This type of contact is governed by the prevailing lubrication and flow in the bearing, creating such fluid film contacts as hydrodynamic lubrication or hydrostatic and many more, each with their respective strength and suitable application.

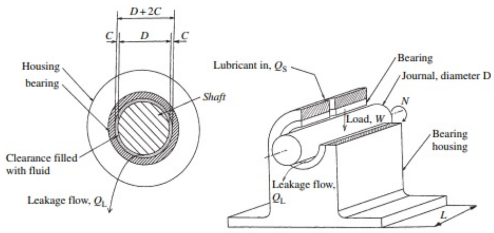

Figure 2.9: Nomenclature and design of a Journal bearing [6].

2.3 Lubrication

The use of lubrication in WEC's presents challenges that are very specific to the conditions of the environment. An important design factor is how to design sealants and lubrication. The lubrication used for the gears is perhaps detrimental as a lubricant for the bearings, therefore, how the system is sealed and modularised needs to be carefully considered. Additionally, if sealants are used, there is a risk of leakage from the WEC into the surrounding environment, or conversely, risk of leakage from the outside into the WEC, possibly reducing life expectancy of machine components in contact.

Chiefly, the types of lubricants can be divided into fluids, solids and gaseous, for fluids, the commonly used grease and oil lubricants, and less common water lubricant. Solid lubricants include molybdenum disulfide, graphite, soft metals etc. Traditionally, the medium used for gaseous lubrication is air due to cost-effectiveness, but other gasses could be used.

2.3.1 Fluid lubrication

Greases, sometimes defined as a thickened oil, rather than a thick oil [15]. More specifically, conventional greases are composed of the base oil with additives (70-95%) and the thickener (5-30%), the composition of greases depends on their application, where more additives or more thickener could be desirable. A Typical strength of greases is the semi-solid structure of the grease, causing the grease to have a higher load carrying capacity. Naturally, some drawbacks exist as well, due to the nature of greases, they do not act as coolants since there is generally not enough flow to transport the heat [16]. Additional strengths and weaknesses for greases exist, where the weaknesses of the grease can be compensated by the use of an oil-based lubricant instead.

The traditional oil lubrication is far less solid than that of greases, where greases can be referred to as thickened oils, oils are hence non-thickened. Although, much like greases, oil lubricants often have additives to improve certain characteristics of the lubricant, such as the friction, carrying capacity or corrosion resistance among others. Additionally, oils are much more efficient at transferring heat than greases. Oil lubrication comes from three different categories of base oil, synthetic oil, mineral base oil (petroleum derivatives) and vegetable oils. In addition to the base oils, different additives are often used, just like in greases. However, an important distinction between oil and grease lubrication is the nature of the load/motion of the application the lubrication is used. With heavy loads and slow motion, grease is the best option. Conversely, if the motion is considered fast (high temperature rise in the contact) together with lower loads, oils are a much better option [17, 18].

2.3.2 Solid lubrication

In situations where fluid lubrication is not suitable, such as in extreme contact pressure environments and high temperature applications (albeit with a short product life), solid lubrication is preferred [19, 20]. Often, these are MoS_2 (molybdenum disulfide) and graphite, although these lubricants can be used to reduce wear, excessive use can lead to abrasive wear and considerable surface damage to the contacting surface [19]. Solid lubrication could work in many different hostile environments, where the key feature is that it does not require a film build-up like other lubricants.

2.4 Near-water/in-water bearing applications

Although WEC technologies are still in the early stages, similar bearing applications to WEC's could serve as a good starting point for these technologies. Such similar applications are hydro power, bearings for water turbines (e.g pelton turbine), ship propulsion systems and more.

Traditionally, sliding bearings are preferred in hydro power, where historically, such bearings could be constructed from lignum vitae, a hardwood indigenous to the caribbean [21]. Although there exist plenty of different replacements with todays technology (polymers, composites etc) that can act as a substitute with equal or better results [22]. However, natural materials such as wood act as a natural composite (fiber resin) and has a natural lubrication, which serves as an additional protection from wear. As a consequence, wood types similar to the lignum vitae is still used today, but not only in hydropower, but also in ship propulsion systems [23].

Additional applications of bearings in ocean environment is on oil rigs and the machinery that goes into it. Where information from oil companies on what bearings are used (for instance in pumps) are sparse, research is conducted to investigate the use of more uncommon bearing construction such as magnetic bearings [24].

2.5 Pelton turbine

One common type of turbine used in fields such as hydropower, is the pelton turbine. Which is the type of turbine used inside the Noviocean (and many other) WEC's, see figure 2.10 below. One similar application of pelton turbines are in the hydropower industry, where it is used as either a horizontal or vertical turbine. Where the primary idea is to use the height difference between the reservoir and the turbine. In this way, the potential energy of the water can be transferred into kinetic energy (high speed jets) and consequently mechanical energy (turbine) However, it could be used for many other applications where a liquid is used to drive a turbine. This type of turbine requires a certain amount of design precision, since the speed of the water hitting the blades has to be controlled in order to harvest energy at a consistent level, namely, the speed of the turbine needs to be half the speed of the initial jet speed of the nozzle [7]. Furthermore, the angle of impact of the water has to be such to idealize the rotation of the turbine. If the water beam hits the turbine blades with incorrect timing or angle, it could result in destructive movement since the analytical model for optimal energy conversion assumes all energy from the jet beam is converted.

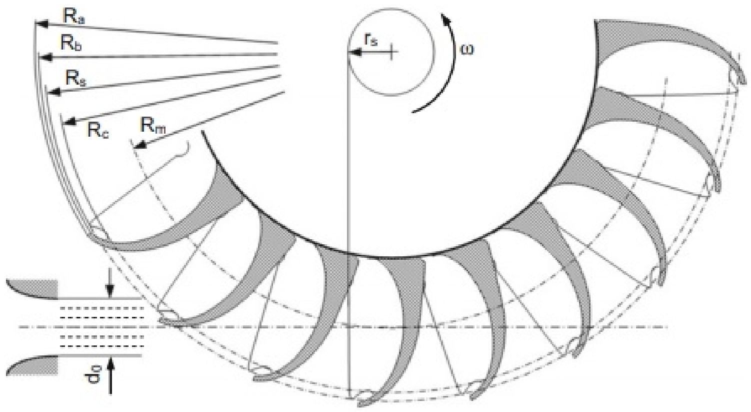

Figure 2.10: Principle design of pelton turbine with nozzle [7].

3. Design parameters & rating model

The investigated aspects of bearing designs in WEC's in this research is summarised into the three main categories below as reliability, scalability and maintenance/lubrication. Rated between 0-1, where 1 is the highest and 0 is the lowest rated value. Additionally, since the different variables have different importance for certain situations, such as how sealing can affect maintenance and lubrication (ineffective sealants leading to lubricant contamination). The rated bearing selections have been modified with weighted values. Where the importance is given the ratings 1.0, 1.1 or 1.2.

3.1 Reliability

Reliability in bearing selections are defined as how survivable a certain bearing selection is, determined through the subcategories fatigue loads, wear and corrosion.

3.1.1 Loads

As mentioned previously, the loads in the systems did not have a detailed force analysis. Additionally, the most important aspect of bearing design is the equivalent load in the contacts. Although the highest possible load in the contact is important as well, to avoid catastrophic failure. The failure modes of bearings in WEC's are according to [25] crack growth, creep fatigue and corrosion fatigue, although each case can vary. For instance, for a semi-submerged WEC device, there could potentially be less corrosion fatigue. However, these are not the only considerations, specifically, surface fatigue is another issue, where an estimate calculation based on the rated life of the bearing in question can provide useful background. Hence, the calculated basic rated life of the rolling element bearings due to fatigue were based on estimated values for the loads and geometry dimensions provided by Noviocean, see Appendix A. The basic rated life for rolling element bearings was calculated following the DIN ISO 281 for oscillating bearings [18] as an estimation for the fatigue life of rolling element bearings. Which can create an issue for scaling as rolling element bearings can require a much bigger diameter than expected.

$$L_{10} = (\frac{C}{P})^p \tag{3.1}$$

For sliding contacts, an equivalent design criteria is the projected pressure onto the surface of the bearing, which is limited by the strength of the material. Assuming there is a uniform pressure exerted on the loaded contact.

$$p_{max} = \eta \frac{F}{dL} \tag{3.2}$$

Where F is the radial force, d is the diameter of the shaft and L is the length of the bearing and η is a safety factor.

Which in turn is limited by material properties, which can be found in the relevant research for the most sensitive materials [8–10]. Which will serve as a background to the possible material and geometry constraints.

The rating for the loads are based on the material and geometry design, where the basic rating life for rolling element bearings are evaluated where a high rated life (highest possible) are the most desirable. Additionally, for sliding contact bearings, the contact pressure was calculated where the material strength properties are the limiting factors. Where a large safety margin for fatigue wear constitutes a good rating.

3.1.2 Wear

Wear initiated for a shaft-bearing contact is heavily influenced by several parameters, such as the type of contact (dry vs. lubricated contact) or the applied load in conjunction with the sliding distance. The different failure mechanisms for bearings due to wear include fretting, adhesive, abrasive, cavitation, corrosive and erosive wear [25]. Where each of these types of wear needs to be understood when choosing bearings for WEC's. Where one of these mechanisms can lead into yet another failure mechanism being initiated. To fairly assess the wear imposed on bearings inside a WEC system the most optimal is to design an experimental study to investigate the wear in a specific system. Since this type of research is rarely conducted, the only way to assess the wear in these systems without an experimental study, is by comparing and evaluating existing research in similar fields to then apply it to WEC's [8, 26–29]. In the relevant research, a large amount of testing has been performed on the use of different polymer composites when using water lubrication [8, 26]. However, the contacts in these cases vary based on what material the counter-face is composed of. In the case of polymer-steel contact, the softer surface (polymer) can exhibit a high wear rate due to the abrasive wear found in this contact. Since the roughness of the steel surface has a high impact on function [30], it creates a high demand on surface finish. Additionally, the conventional research targets rotating shafts/bearings, whereas in a WEC, the motion would be oscillating. This in turn means that in order to fully model the wear behavior and damage modes in those contacts, extensive investigation into oscillation in conjunction with the prevailing environment [31] would be required. The evaluation rating for the wear was based on how the wear and friction in the contact based on different lubricants and materials.

3.1.3 Corrosion

Corrosion is commonly classified as wear [17]. However, since corrosion carries such an importance when exposed to the ocean environment, it is evaluated here separated from wear since the method of how to counteract corrosion and other wear mechanisms is not necessarily the same.Although corrosion models exist, such models include complicated analytical and numerical models [2] which may not be applicable to every situation. However, plenty of research has been made into different corrosion resistant materials and which materials are more suitable in different corrosive environments [8,27]. For the application of seawater submerged components or structures, the anti-corrosion coatings play a very important role for the reliability and longevity of the components. Improper or insufficient design consideration, including anti-corrosion coating of important components can lead to devastating failure mechanisms [27]. Typical corrosion mechanisms are fretting corrosion and pitting corrosion. Where fretting corrosion typically occurs when there is low-amplitude oscillatory motion in the tangential direction between two contacting surfaces (which is normally at rest) [17]. Commonly seen in most machinery where vibrations occur. However, special consideration must be taken when considering pitting corrosion, where such corrosion can occur at a sub-surface stage, and therefore not as visible as other types of corrosion/wear mechanisms [27]. The corrosion resistance of materials in the evaluation were evaluated using existing knowledge about corrosion and which materials handle marine corrosion most effectively.

3.2 Scalability

The scalability of bearing designs was evaluated based on the geometry, the more complicated it is to scale the bearings, the less scalable they would be. As an example, a sliding bearing has very good scalability since the geometry is based on the length/diameter ratio, where this ratio is ideally 1, which means that prototype testing vs full scale testing is very similar since the prototype should be scaled equally.

Another factor that plays a role in scalability is the rotational speed and diameter of the rotating shaft. Called "DN-number", it represents a numeric value for what can be seen as a fast or slow rotational speed. Using the geometry based on information provided by Noviocean, equation 3.3 leads to a linear relationship with the increase in diameter.

$$DN = (Bore\,diameter(mm))\ \text{x}\ (rotational\,speed(rpm)) \tag{3.3}$$

Where the rotational speed is evaluated from 3.4 as shown by [18]. Which results in a DN number <1000, by comparison, a limiting rpm value for rolling bearings is between $5 * 10^5$-10^6. Meaning that using this method, the speed of the speed can be considered very slow.

$$n = n_{osc}\,\frac{\phi}{180} \tag{3.4}$$

Where n_{osc} is the frequency of oscillation, and ϕ is the oscillating angle.

Additionally, the scalability is affected by both the load and load direction, where in the case of rolling element bearings, the contact angle for the applied load on the raceway changes based on the size of the rolling element and raceway. Similarly, in the case of a journal bearing the contact changes based on size, although in a less complicated way than for the rolling element contact since the contact area ratio would remain the same.

3.3 Maintenance & Lubrication

Much like how corrosion is related to wear, lubrication is related to wear as well, where the lubrication regime and choice can impact the wear. However, since lubrication has a large importance in the WEC application, lubrication itself will be rated. The lubrication of the bearings has different ways to be designed, one important factor of it is sealing. If the bearing is sealed, grease or oil would have to be used, however, if no sealing was used, the bearing could potentially be seawater lubricated. In contrast, a sealed bearing would inevitably need maintenance due to sealing of the bearing cannot offer a complete filtration of contamination or prevention of leakage [6]. However, the use of multiple seals could alleviate the issue of leaking completely during an assigned time period which would improve how applicable sealed bearings would be in WEC's. Furthermore, using a bearing with grease or oil lubrication demands extensive control over potential water contamination in the lubricant, since water contamination can lead to a wide array of failure mechanisms [32]. Additionally, an important factor is the motion of WEC's, if the motion is considered slow and of oscillatory nature, the lubrication efficiency of oil is drastically reduced. Since the oil may have issues fully coating the surface as effectively as if the motion was fully rotational. Since the maintenance and lubrication is related to each other, the rating of these two are joined together, where they are both evaluated by applicability and how well the lubrication performs under load for the applied conditions.

3.3.1 Cleaning

Cleaning, often in conjunction with general maintenance, is partly the removal of unwanted particles and other contaminants that could cause issues in the contacts. These contaminants could cause severe abrasive wear if they set into the contacts [16, 19]. Meaning for an open system, larger particles could enter the contact zone for the bearings, such particles could include sediment from the ocean floor, sand or even pollutants. Due to this, cleaning is evaluated at how important cleaning is for a certain bearing design.

3.4 Rating model

In research, the terms reliability and validity refers to how well the methodology is implemented during testing. Where reliability refers to the precision, and validity refers to the accuracy. For this report, the reliability and validity refers to two things, firstly, the research found during the literature review. Secondly, the ratings that are set on the bearing selections. Using the information gathered from relevant research, a rating is given to a certain bearing selection and subsequently weighted as shown in equation 3.5. Resulting in a rating based on the research provided.

$$R = r^I \tag{3.5}$$

The importance subsequently lowering any rating less than 1. Additionally, this model can be extended to statistical calculations where R is the calculated mean, median, standard deviation, range and upper and lower quartile [33] and r is the given rating. Note that these are represented conveniently using a box plot in this report except the standard deviation, however it is included here to show how the model could be applied to the standard deviation.

$$R_{\text{mean}} = \frac{1}{n}\sum_{j=1}^{n}(a_j r_j)^{I_j} \tag{3.6}$$

$$R_{\text{median}} = \frac{(a_j r_{\frac{n}{2}})^{I_j} + (a_j r_{\frac{n}{2}+1})^{I_j}}{2} \tag{3.7}$$

$$R_{\text{std}} = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(a_j r_j)^{I_j} - \frac{1}{n}\sum_{j=1}^{n}((a_j r_j)^{I_j})^2} \tag{3.8}$$

$$R_{\text{range}} = (a_n r_n)^{I_n} - (a_1 r_1)^{I_1} \tag{3.9}$$

For all elements $\{r_1, r_2, r_3 ... r_n\}$ as given ratings on design parameters: wear (1), corrosion (2), load (3), scalability (4), lubrication (5) and cleaning (6). Where R denotes the calculated, weighted rating, r denotes the rating given to a design parameter, I denotes the weighting (importance) and a denotes a scaling factor. In this report, a is set to 1, however, the model can be applied to use this factor instead of I or be used as a different scaling factor.

The 1st and the 3rd quartiles were determined through the median of the lower and upper quartiles which in turn was determined by the median calculated in 3.7. Another potential method that was investigated to show the rated types was using the standard deviation and range only. However, this method was disregarded in favor of a box plot since that is more common practice and is more widely known easy to read. In addition, using strictly standard deviation for a set of observations less than 10 would not be as appropriate. Furthermore, the rating given to each bearing type was affiliated with how applicable said type was, this was summarised in table 3.1 below. Where the bearing rating scale is explained for five different intervals and what those ratings mean specifically.

Table 3.1: Given rating and its meaning

Rating	Implications
0.0-0.2	Parameter is viewed as having poor performance or lacking research validation for the given bearing type.
0.2-0.4	Parameter is viewed as having poor/moderate performance and lacking somewhat in research validation for the given bearing type.
0.4-0.6	Parameter is viewed as having moderate/good performance and having moderate/good research validation for the given bearing design.
0.6-0.8	Parameter is viewed as having good/very good performance and having good/very good research validation for the given bearing type
0.8-1.0	Parameter is viewed as having excellent performance and having excellent research validation for the given bearing type.

3.5 Survey questions

The survey construction was designed to provide some validation and to reflect the complexities of the challenges in the research topic, issued and presented in parallel to the bearing evaluations. The questions that was issued can be shown below. In addition, the load/motion conditions are the same as the motion and load used for the calculations in this report. Which in turn is based on the Noviocean case as expressed in Appendix A.

- On a scale of 1-5 (where 1 is the least, and 5 is the most), how applicable do you think a sliding bearing could be in WEC's?
  - Please add a short description of the reasoning behind your previous answer as well as how certain you are of your answer.
- On a scale of 1-5, how applicable do you think a rolling element bearing could be in WEC's?
  - Please add a short description of the reasoning behind your previous answer as well as how certain you are of your answer.
- On a scale of 1-5, how well do you think oil lubricants could work as lubricants for bearings in WEC's?
  - Please add a short description of the reasoning behind your previous answer as well as how certain you are of your answer.
- On a scale of 1-5, how well do you think grease lubricants could work as lubricants for bearings in WEC's?

  - Please add a short description of the reasoning behind your previous answer as well as how certain you are of your answer.

- On a scale of 1-5, how well do you think seawater as a lubricant could work for bearings in WEC's?

  - Please add a short description of the reasoning behind your previous answer as well as how certain you are of your answer.

- What type of material(s) (or material composites) do you think is most applicable to WEC technologies?

  - Please add a short description of the reasoning behind your previous answer as well as how certain you are of your answer.

- Finally, in a short description, what kind of bearing design do you think is most applicable for bearing designs in WECs? Combining the bearing contact, material and lubricant.

Where the goal of the survey was this; what is the perception on different lubricants, material choices and sliding/rolling bearings for WEC technologies.

4. Result

4.1 Bearing design evaluation

The motion and load case for the evaluated designs are based on the information provided by Noviocean. Due to the sensitivity of the information, the specific values cannot be shown, but similar example values are used in Appendix B. The loads of the system are illustrated using figure 4.1 for sliding bearings, where selected materials are showed in relation to the L/D ratio for the bearing/shaft.

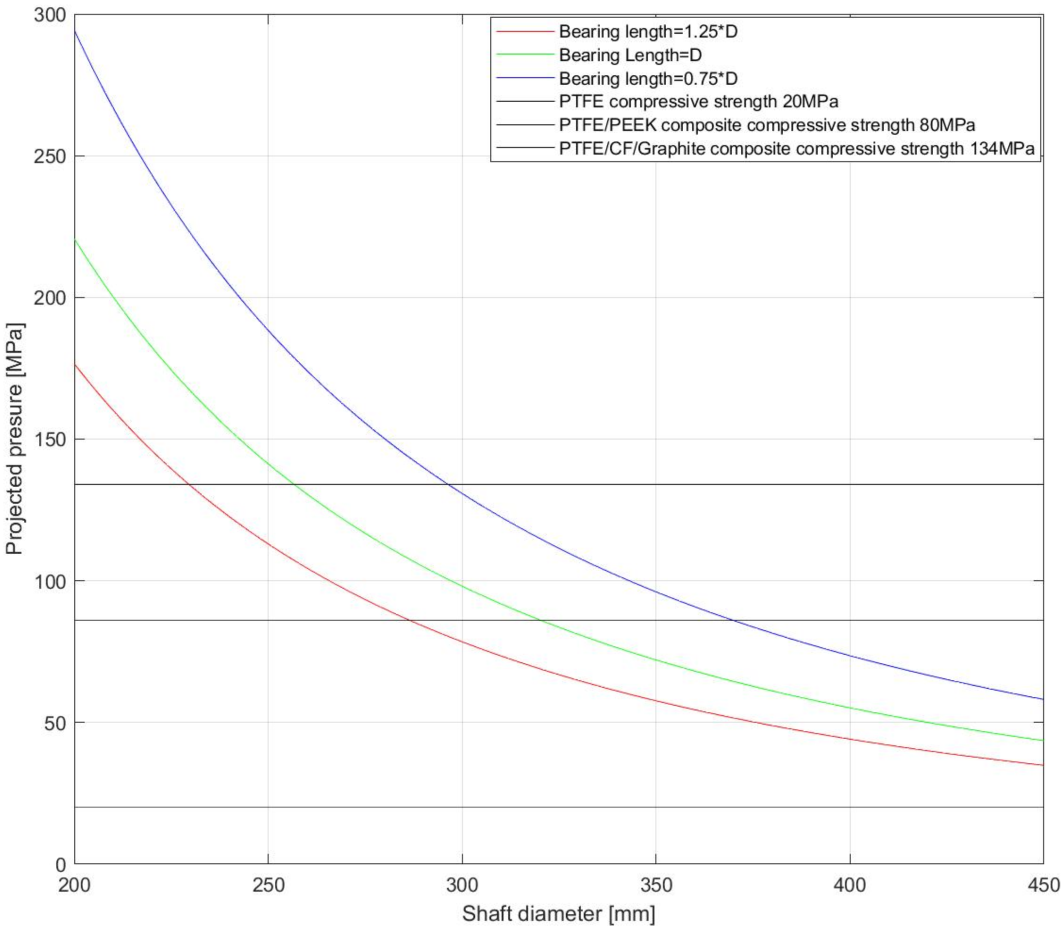

Figure 4.1: Projected pressure as a function of shaft diameter with safety factor 3 with examples of compression strengths [8–10].

For the case of rolling element bearings, the calculated basic rating for a roller bearing resulted in a dynamic life rating which would need to be specially designed (~8400kN). Where the only bearings that could accommodate the loads for this case was spherical and cylindrical roller bearings (according to bearing catalogues from Timken, SKF and FAG). Subsequently, for a ball bearing the estimated rated life is ~9400kN.

4.2 Rating procedure

To summarise the rating procedure for each bearing type, two examples are used to illustrate the process. The same process is conducted for each bearing type. The first example, being the type 1 bearing presented in 4.2 (seawater lubricated polymer composite sliding bearing).

The second example is type 9, a sealed, greased (for life) stainless steel rolling element bearing.

4.2.1 Wear rating

Example 1

"Investigating the possibilities for using “better” materials or developing lubricating fluids which are inherently less harmful to the environment are other options whilst the “holy grail” is the use of water as a lubricant." [22]. Which illustrates the desire to use water as a lubricant wherever and whenever it is suitable but also its limited field of use. Additionally, wear in general for certain polymer-steel contacts is not ideal for saltwater lubrication [28]. However, plenty of research would indicate that for particular polymer composites for specific contacts (e.g super polished steel contact), the wear can be manageable even under oscillating conditions [11]. Additionally, according to [30] the most important factor affecting wear in polymers under sliding is the surface topography of the counter face. As the research indicates that different views exist on how applicable polymer composites could be, it was given a rating of 0.5, and the importance to 1.2.

Example 2

For the second example, many design parameters are reduced to the same case as for a regular greased contact [6]. Therefore, the wear rating is very similar to a more regular case, barring the oscillating motion [34, 35]. Which illustrates the complexity of the oscillating motion and wear combined. Due to using grease in the contact, the applied load is significantly reduced in the contact [34], which consequently reduces the wear to some extent. Since the conditions for this bearing is similar to a regular case, but with dependence on the other design parameters, it was given a rating of 0.7, and the importance of 1.2.

4.2.2 Corrosion rating

Example 1

"Hence, seawater itself exhibited a better lubricating effect than pure water..." [8] explaining how the effect of corrosion caused the wear rates and friction to be increased due to the use of saltwater, however still equivalent to pure water. Additionally, the naturally corrosion resistant polymer material show high viability in marine environments [9, 11], and is currently being used in some applications [12]. Due to how well received polymer composites are to corrosion resistance, it was given the rating 0.7, and the importance of 1.2.

Example 2

The corrosion parameter for type 9 is in general good since stainless steel is a commonly used material for anti-corrosion. However, the main perpetrator of corrosion is time, where stainless steel, given enough time, will corrode, often faster than perhaps expected [2]. In the context of corrosion, corrosion induced wear rates in the bearing contact can be disregarded [27]. Where a sealing would eliminate that type of mechanism. Due to the nature of the environment, some corrosion may still occur on the outside of the bearing, which could potentially have consequences [27]. Since stainless steel is a decent option and that the contact itself is protected, however it can still have outside influences, the corrosion rating was set to 0.7, and the importance to 1.1.

4.2.3 Load rating

Example 1

Polymer composites suffer slightly in the load category when compared to other materials since the strength of these polymers are not as high as e.g stainless steel as Shown in 4.1. Which leads to polymers having a smaller margin for safety from fatigue loads than other materials. However, due to how a sliding bearing functions [6], it is possible to scale and redesign sliding bearings relatively easily. Another important parameter for sliding bearings is the PV-value [6], which restricts the speed/pressure ratio for a certain material (too hot and it starts to deform). In this application however, the speed is very slow as shown in equation 3.3 such that the temperature presumably is not an issue. The load rating for a polymer sliding bearing consequently was given the rating 0.5, and the importance to 1.1.

Example 2

Due to the application of grease in the type 9 contact, the applied load is significantly reduced [34]. Additionally, according to the calculated load rating from 3.1 the fatigue loading of the roller bearing is adequate. Furthermore, the loading of a rolling element bearing in high loaded oscillating conditions have not been researched deeply, certain findings points to subsurface plasticization can occur leading to cratering in contact due to fatigue yielding of the surface layer [36]. As such, the load rating for type 9 was set to 0.8 and the importance to 1.1.

4.2.4 Scalability rating

Example 1

Scalability of different bearings focuses mainly on how easy/hard it is to scale them. Where in this report, these bearings are either rolling element bearings, or sliding bearings. Meaning that all sliding bearings share the same rating, and all rolling element bearings share the same rating. The main factor in scalability is the scaling of the pressure in the contact, which can be represented using the Hertzian contact pressure [17]. Which for a sliding bearing is a conformal line contact and is relatively straight forward to scale, therefore the rating for this was set to 0.9. Since the scaling of bearings have a massive importance in prototype testing and experimental testing, this design parameter should be investigated thoroughly when implementing bearings in WEC's. As such the importance was set to 1.1.

Example 2

For type 9, the scalability is as stated earlier, slightly more difficult due to the nature of the contact for a rolling element bearing [17]. However, since the scaling of the bearings is purely a modeling issue rather than a system parameter issue that other tribological parameters face, it can be thoroughly modeled beforehand to avoid any issues. As such the scalability rating was set to 0.8 and the importance to 1.1.

4.2.5 Lubrication rating

Example 1

The lubricating effect of saltwater has different important aspects to it. One of these is the corrosion of the counter face, where seawater has a large amount of Cl^- which leads to rapid corrosion of steel [28]. However, the environmental benefit from using water as a lubricant cannot be understated as it would remove the potential need of oils or greases, and especially if seawater could be used [22]. PTFE-composites in particular have a self-lubricating effect as well [6, 19] which can further improve the use of a water lubricant since the material already has low friction in a dry contact. Saltwater/water as a lubricant is only effective if certain material composites are used, however, the environmental benefit of this type of lubricant results in a rating of 0.6 and the importance of 1.2.

Example 2

Lubrication for type 9 is centered around the use of grease lubrication. This type of lubricant is much like oil, sensitive to water contamination, where small percentages of water can cause the lubricant to fail in its lubricating properties [16, 32]. Furthermore, greases can improve the loading capability of greased contacts [6, 34]. Additionally, greases have the added benefit of being able to protect the lubricated contact from particle contamination such as sand or others [6]. Therefore the lubricant rating is set to 0.8 and the importance to 1.2.

4.2.6 Maintenance rating

Example 1

Maintenance/cleaning of the bearings are heavily dependent on external factors. For instance, a saltwater lubricated bearing can be subjected to salt particle, sand or other pollutants be driven into the contact [9]. Where these can lead to abrasive wear, 3-body rolling contacts and other detrimental effects. Additionally, since the wear mechanisms in these contacts are mainly abrasive [28]. Since maintenance would be required to a moderate extent due to particle contamination, the given rating was 0.5 and the importance to 1.2.

Example 2

The maintenance of greased contacts can be very little for certain conditions, as greasing for life is a possibility. However, for this type of bearing and application, the requirement on sealants become very high as unnecessary contamination of the contact would lead to a more frequent cleaning/maintenance interval [17,32]. Meaning that if sealants are not effective enough, grease spilling, oil spilling, lubricant contamination etc can be a devastating factor [6, 37]. As such the maintenance rating was set to 0.6 and the importance to 1.2.

The two examples shown are used as an example of how the methodology is employed for all bearing types, furthermore, the rating for each bearing type are shown in Appendix C.

The complete evaluation for all bearing selections can be seen in figure 4.2 below represented as boxplots for each given type.

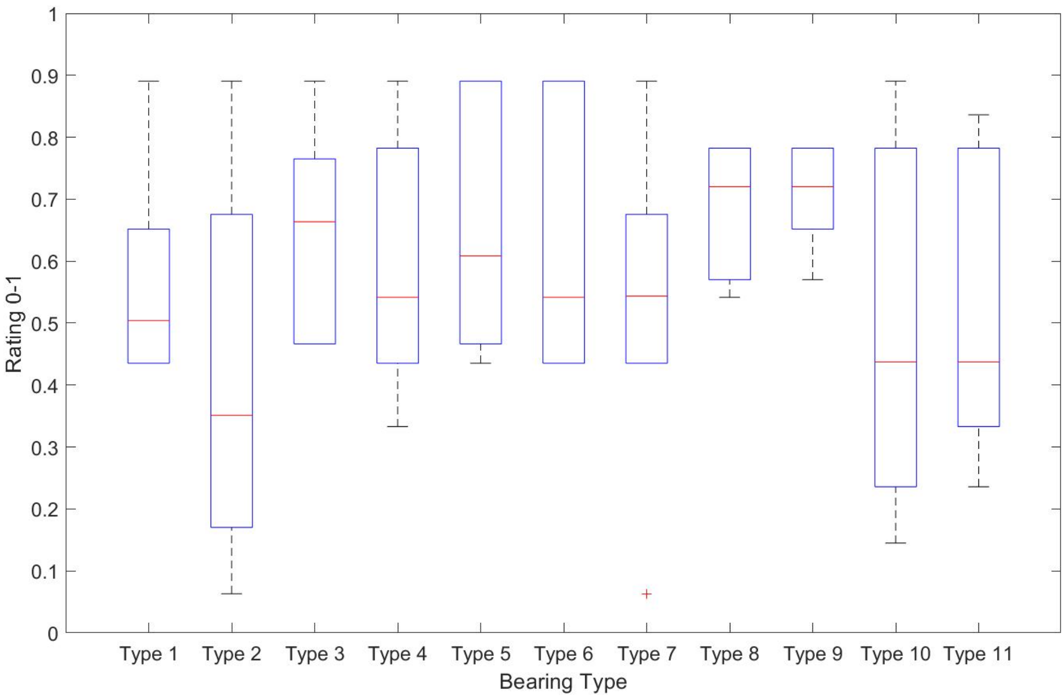

Figure 4.2: The evaluated bearings shown as boxplots for each type.

Where the different types represent the bearing designs that are shown in table 4.1 below. Where all contact will be against a steel shaft (as per a design constraint), with the assumption of good corrosive protection coating on the shaft surface. All evaluated bearings for the boxplot can be shown in Appendix D. Where the results shown in the boxplot graph illustrates clearly the

Table 4.1: Table summarizing bearing design types.

Type	**Description**
Type 1	Seawater lubricated polymer composite sliding bearing
Type 2	Dry, sealed polymer composite sliding bearing
Type 3	Sealed and greased (for life) polymer composite sliding bearing
Type 4	Seawater lubricated stainless steel sliding bearing
Type 5	Sealed Oil-lubricated ceramic sliding bearing
Type 6	Water lubricated ceramic sliding bearing
Type 7	Water lubricated bronze sliding bearing
Type 8	Sealed and greased (for life) ceramic roller/ball bearing
Type 9	Sealed and greased (for life) stainless steel roller/ball bearing
Type 10	Water lubricated ceramic roller/ball bearing
Type 11	Water lubricated stainless steel roller/ball bearing

difference between a sealed bearing and a water/seawater lubricated bearing.

4.3 Survey Result

Furthermore, the results shown from the survey issued to industry professionals can be seen below.

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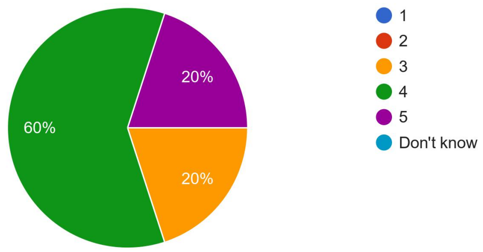
Bearings in wave energy converters

5 responses

On a scale of 1-5 (where 1 is the least, and 5 is the most), how applicable do you think a sliding bearing could be in WEC's?

5 responses



Please add a short description of the reasoning behind your previous answer as well as how certain you are of your answer.

5 responses

As long as the load is spread sufficiently polymer bearings could have a role to play as corrosion could be limited.

Roller bearings have issues with salt water and oscillating slow movements, combined with high loads

large diameters, high loads, enough space around the joints

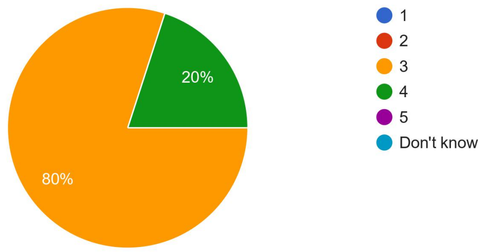
I think sliding bearings can find applications as similar applications already use them. The possibilities in terms of material, scalability and water lubrication offer advantages for use in WEC. Disadvantages could arise during maintenance. The design possibilities of sliding bearings are limited compared to rolling element bearings.

Low speed and reciprocating motion makes sliding bearings suitable as long as the supplier can guarantee the life.

https://docs.google.com/forms/d/1Y7USpUUB1ax1Z611eoeh_YVRbkoUMcL9J0aqPD2ygWc/viewanalytics 1/7

On a scale of 1-5, how applicable do you think a rolling element bearing could be in WEC's?

5 responses



Please add a short description of the reasoning behind your previous answer as well as how certain you are of your answer.

5 responses

Corrosion protection in some form would be required.

In our solution nice for the turbine and generator

around the turbine and the topside structures, yes

Rolling element bearings have been used successfully in wind turbines under comparable conditions. With suitable sealing technology, in my opinion, the most promising solution due to the multifaceted applications and design solutions.

Rolling element bearings can do the job but probably they become larger end more expensive.

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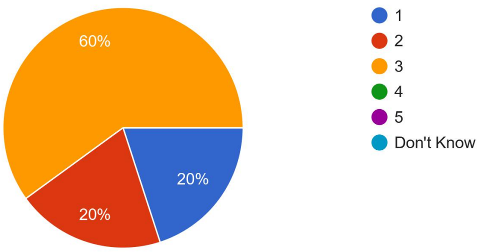
On a scale of 1-5, how well do you think oil lubricants could work as lubricants for bearings in WEC's?

5 responses



Please add a short description of the reasoning behind your previous answer as well as how certain you are of your answer.

5 responses

As long as the system is isolated from the sea, mineral oils / greases (and others) could be used.

Not my speciality, so unsure. (Jan)

for some of the bearings, yes.

Due to the oscillating motion of the entire system and the alternating loads, it isn't easy to have the lubricating oil where it is needed. Using lubricating oil without regular maintenance and/or a lubrication system should also prove challenging.

Oil lubricants will put high demands on sealing solutions. Due to the reciprocating motion the oil might not be distributed to the contact zones.

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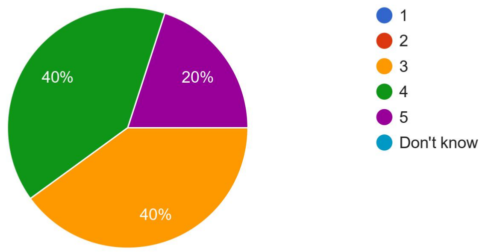
On a scale of 1-5, how well do you think grease lubricants could work as lubricants for bearings in WEC's?

5 responses



Please add a short description of the reasoning behind your previous answer as well as how certain you are of your answer.

5 responses

Probably more controllable than oils, but re-lubrication is probably required.

x

for the large journal bearings, and for small roller element bearings

Lubricating greases are already used in similar applications. An application is conceivable if the sealing system is fully functional. To ensure the system's longevity, new lubricants, especially for WEC, have to be designed.

I guess that grease is less sensitive too small amounts of water contamination than oil. Grease will also easier stay in the contact. However, it might be necessary to design a system where new grease recurrently is pressed into the bearing.

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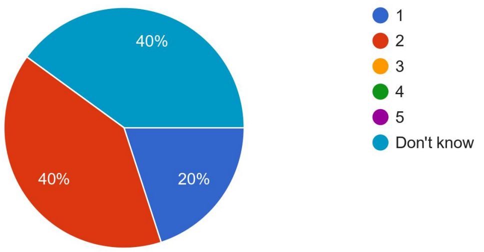
On a scale of 1-5, how well do you think seawater as a lubricant could work for bearings in WEC's?

5 responses



Please add a short description of the reasoning behind your previous answer as well as how certain you are of your answer.

5 responses

It depends on the bearing, but sea water is used in other marine applications.

x

very poor properties as lubricant

Due to the lack of literature or comparable applications, I find it difficult to give an assessment. Still, I think the possibility is promising.

I am very unsure about using sea water. It is worth investigation since it would be a perfect lubricant. Water has been reported to have extremely low friction in sliding bearings made by ceramics. Also polymers might be a possible material.

https://docs.google.com/forms/d/1Y7USpUUB1ax1Z611eoeh_YVRbkoUMcL9J0aqPD2ygWc/viewanalytics 5/7

What type of material(s) (or material composites) do you think is most applicable to WEC technologies?

5 responses

Polymers are commonly used at the moment, but other novel combinations could be explored, for example, carbon composites with solid lubricants embedded in the materials.

x

stainless steel, corrosion resistant bronzed. advanced polymers

I think any material combination is possible.

Depends on the design strategy. Any common bearing material can be used if water is kept out by seals or pressurized bearings. If a fail safe strategy is used a material that can handle salt water must be used. I do not know which materials that have this property.

Please add a short description of the reasoning behind your previous answer as well as how certain you are of your answer.

5 responses

As far as I know, composite materials are not well explored for marine applications.

x

corrosion as a result of exposure to the elements.

There is a wide variety of polymers and composites available. Stainless steel and coatings have long been used successfully.

I am not sure about this at all.

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Finally, in a short description, what kind of bearing design do you think is most applicable for bearing designs in WECs? Combining the bearing contact, material and lubricant.

5 responses

Non-metals.

I am open to your suggestions

grease lubricated bearings with grease-for-life systems

A greased rolling element bearings with WEC adapted sealings.
Probably as a multi-row cylindrical roller bearing, similar to wind turbine pitch bearing of the multi-megawatt class.

My guess is that sliding bearings are best for this application. Best would be a material combination that allows salt water as lubricant and if this is not possible grease lubrication which allow some salt water contamination. If necessary, a totally sealed design with grease lubrication must be used.

Where the answers to these questions provide a background and validation to the different design parameters and the challenges therein. Additionally, the number of participants were 5 as shown in the result figures.

5. Discussion

Several factors impact the discussion of this report since the field of WEC's is yet to be fully explored and detailed. The idea of seawater lubrication of WEC bearings comes from the development of technology suited for the environment. Similar to the development of stern tube bearings in naval ships or similar [23, 38]. Where a seawater lubricated bearing is made for hostile operating environment, which a sealed bearing solution does not necessarily achieve. To that end, plenty of research into polymer composites have been conducted to verify viability of such materials when exposed to water lubricated regimes, where polymer composites have become massively more powerful and viable than before [11]. This is reflected in the result shown for the evaluated bearing selections. Where the water lubricated bearings have a large potential [9, 11] (type 1,4,6,7) shown in the ranges in figure 4.2 but with a lower median compared to others. Additionally, some application could be found for wood bearings as it has been shown that these have a certain degree of relevance in water lubricated contacts [21, 23]. However, using efficient sealants (multiple high grade sealants) can be sufficient to avoid water contamination in the lubricant such that a greased or oiled bearing solution can work sufficiently. Another benefit of a sealed bearing over seawater lubricated bearing is the issue of sediment/sand/pollutants inside the contacting surfaces. This could lead to unexpected failure mechanisms such as abrasion from ocean sediment or unforeseen corrosion mechanisms from pollutants. For the evaluated bearings, this can be seen in type 3,5,8,9 which show that a sealed bearing have a higher median but also a lower range than that of a water lubricated bearing [26, 34].

The negative effect of using multiple sealants is the effect of friction on the overall power produced in the WEC. Where the LCoE (Levelized Cost of Energy) of WEC's are currently sensitive to decreases in produced energy, and increases in cost of production, costly sealing solutions could worsen this situation. Additionally, the issue of corrosion has a palpable effect on the bearings and all other systems in WEC's, material and coating choices has a huge impact on the efficiency and survivability of the entire WEC and bearings specifically [39].

An important comparison made in the report is a sliding bearing against a rolling element bearing. Where the different bearings both have advantages and disadvantages. The sliding bearing is traditionally more suited for oscillating motion, albeit with a higher startup friction [6]. But, the rolling element bearing is currently used in wind turbines that have somewhat similar environments, with the exception of the high corrosion. This means that the implementation of bearings in WEC's can potentially make use of the already gained knowledge from wind energy. Furthermore, when concerning oscillating motion, a sliding bearing is a more efficient use of material as in rolling element bearings, not all rolling elements are in a loaded contact during the lifetime of the bearing.

A very important aspect when referring to the application of bearings in WEC's is the cost. Which was not included as a research/design evaluation topic, but is highly important nonetheless. If certain bearing solutions are regarded as too expensive or risky, those types of solutions will not be utilized in the industry. Additionally, specific solutions to material or design of bearings can sometimes not be commercially available, which means that even if there is an interest in more novel materials or designs in research, such materials might not be commercially available. Another cost related issue is that of lubrication and sealants. Typically, the higher the performance of a sealant/lubricant is, the more expensive it is. Even though certain perfect solutions might exist, they might be very expensive for the customer [13].

5.1 Survey discussion

The result of the survey show interesting results, where some responses were expected, others showed interesting reasoning behind the responses. However, the consensus is that both sliding bearings and rolling element bearings could work, but heavily dependent on the design. The survey reflects how complicated and how many aspects there is to consider when designing bearings for harsh conditions. Where each aspect to some extent is dependent on other aspects, resulting in a complex system.

The first question seeks to investigate what the perception is around sliding bearings, where the consensus is that sliding element bearings have the potential to be better than rolling element bearings. Where certain conditions would make the sliding bearings better; high loads, oscillating motion and high corrosion. However an important factor which is not mentioned in this case is the start-up friction for sliding bearings. Because of the reciprocating motion, the motion starts and stops and causes the sliding bearing to be influenced more by the reciprocating motion.

The second question; how applicable a rolling element bearing could be, showing that in comparison to the sliding bearing, the majority rated it slightly lower. Where corrosion protection becomes very important, and an added negative is the increase in cost due to the larger diameter of the rolling element. Where the question of cost is an ever-important issue for emerging technology. Equivalent to the previous comment about the start-up friction, what is not mentioned by any participant is the start-up friction, where rolling element bearings have a much lower start-up friction than a sliding bearing.

The third question handles the issue of oil lubricants, where the general consensus is that it is a moderate to poor lubricant. Where an important factor is how the lubricating oil is supposed to have the lubricant reach the entire contact area if the motion is oscillating. Additionally, the use of sealants become even more important since accidental oil spilling has to be a no-factor. Another important factor in the use of oil lubrication is the maintenance required, where regular maintenance would be needed.

The fourth question talks more about grease lubricants, where there is some division in the rating. Where the consensus here is that a grease lubricant could work well or excellently in the conditions. However some re-lubrication would be required. The use of grease lubrication in a rolling element bearing is seeing current use in wind power, which to a certain degree proves the concept to be viable. Here the participants have not mentioned the effect of the oscillating motion on the grease, whether or not it is viable. Where the oscillating motion can prove to be an issue, however, most likely less of an issue than in the use of oil.

The fifth question, often seawater lubrication has been brought up in this report to assess how viable it could be and the qualities and beneficial properties has been stated several times. The consensus here is that seawater as a lubricant is either very poor or not enough information exist to assess its viability. This shows not only the fact that seawater as a lubricant is very unexplored territory, and the fact that as a standalone lubricant, it can be considered very poor. However, with particular material combinations, it has been shown in this report that it could work in certain applications, but more experimental data is needed within WEC parameters.

The sixth question pertains to what type of materials could be applicable. Where different input is given to plenty of different materials. A very interesting input which is partly the goal in this report, is that it depends on the design strategy. As stated earlier, in the example of a polymer sliding bearing, saltwater could work, but for any metallic alloys it would be inappropriate. Furthermore, very efficient sealants can lead to any material combinations being possible. To reach a consensus on this issue the combined input leads to any material being possible but composite materials need to be explored more for marine applications if such are to be used.

The seventh and last question attempts to summarise the participants thoughts into one type of bearing design that could work. The wide consensus is that greased bearings would be well suited to the application, however, when it comes to whether a rolling or sliding bearing is best, there is no clear consensus. This is most probably due to the fact that the participants have different knowledge bases for certain contacts, where they are colored by their research history.

For this survey, it was preferable to have more participants, however, the current participants had somewhat similar views, although with some interesting deviations. Having a few more participants nonetheless would help solidify those views more. Additionally, an important note for this kind of survey is the fact that specific boundary conditions are missing, even though the information given is sufficient to make some observational assumptions. Yet more detailed information would help create a more holistic view, which was unfortunately not in the scope of this project.

5.2 Future work & improvements

Firstly, the improvements, the thesis covers several important topics, however, it can be more detailed in certain aspects. With that being said, the challenge of creating a review on the topic chosen is exactly that, the lack of specific research into bearings in WEC's. Therefore, how to apply research from similar fields to wholly complete a review becomes challenging. Another improvement is how the rating was determined, where another additional depth to the rating could be to rate each individual found research on a rating scale for each design parameter. After which compile all these ratings into a calculated mean based on individual research papers.

The future work of the research topic is something that is of particular interest since the wave energy field is gaining more and more traction. The coming work associated at the university entails experimenting with different bearing designs to investigate things like the wear behavior or sealing solutions and other important design factors. Additionally, an interesting topic for experimenting with is seawater lubricated bearings. Currently the application of such a design seems inappropriate with the lack of testing and verification. But with the continued testing of such designs it could prove to be both an environmentally friendly and cost-efficient solution. Furthermore, instead of using sealants, the use of a filtration device would be necessary to filter out the larger particles that could enter the surface contact of the bearings. Which presents another design topic, how and where to implement such a filtration device and how effective they could be, possibly eliminating one of the issues of seawater lubrication; foreign particles. Conversely, the investigation into different sealing solutions can prove to be an interesting area as well. Where different sealing solutions and improvements into sealing technology could help aid other applications where sealants are a necessity. Another valuable input is the use of hybrid bearings, where these types of bearings have barely been explored for the given application. Where hybrid bearings can offer benefits from different positively evaluated materials and contacts.

6. Conclusions

The study has focused on the literature review and investigation of potential bearing designs and design considerations for a specific application that has not yet been fully explored, namely bearings in WEC technology. And to a further extent, tribological properties in WEC technology. In order of the listed research questions, the conclusions are:

- Why does the choice of lubrication impact the reliability of bearings in WEC designs?
  - The lubrication regimes and properties of different bearing solutions heavily depend on the design approach, as an example, a sealed and greased (for life) bearing, is heavily dependent on the sealing of the bearing. If such bearings are designed to be grease lubricated, potential contamination of the lubricant can have dire consequences, where the effect of water contamination on lubricants have been researched extensively in the past.
- Why does scalability impact the choice of bearings in WEC's?
  - How scalable different bearings are depends on a case-by-case basis. Where there are plenty of limitations to bearings and geometry, most notably to the diameter of the shaft and the load on the bearing. In the presented case (3MN loaded bearings) a rolling element bearing would need to reach around a 480mm diameter shaft. Furthermore, the same issue persists for sliding bearings, although sliding bearings can be scaled more easily, making prototype testing more straightforward.
- Why does different bearing materials impact the potential reliability of WEC's?
  - Different bearing materials have been seen to affect the wear properties greatly (as expected). However, the extremely hostile environment of the ocean (even more so for a submerged component) poses an exceedingly difficult design challenge. Where not only the salt content in the ocean plays a factor, but also the organic matter in the ocean which can both contribute to increased wear rates of the materials.

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A. NoviOcean load parameters

The prescribed motion and loads were based on the estimated values provided by Noviocean.

- Load applied on the bearing contact estimated at 3MN.
- Motion defined as oscillating with average 40 degree oscillating angle, 10000 cycles/day.
- Total bearing life aim at 20 years (5year maintenance period).
- Shaft diameter as 200mm-450mm.
- Bearing location close to seawater/submerged in seawater, high exposure to seawater corrosion.

B. MATLAB code

MATLAB code used for calculations and evaluation of bearing selections including weighted values.

```
%Master thesis bearing calculations
clc, close all, clear all,
%%
%rolling element bearing life
cycles=10000;                           %cycles/day
n=(10000/(24*60));                      %oscillations/min
d=200:1:450;                            %shaft diameter mm
r=d/2;                                  %shaft radius
L_min=0.75*d;                           %min. bearing length
L_max=1.25*d;                           %max. bearing length
phi=40;                                 %oscillating angle
a_roller=10/3;
a_ball=3;
life=24*365*20;                         %life in hours
L_10h=life;
load=300*10^3*9.81;                     %newton
n_osc=n*phi/180;                        %Harris 1

F_re=load*(40/90)^(1/a_ball);

c10=F_re*(60*n*L_10h/(10^6))^(1/a_ball)*10^-3   %Load rating kN
DN=d*n_osc;


%%
%sliding bearings projected pressure
R=zeros(1,251);
Rm=R+20;                                %Compressive strength from literature
eta=3;                                  %safety factor

freq=n/60;                              %Hz
arc_length=r*(2*pi*2*phi/360)*10^-3;    %arc length of shaft/bearing diameter [m]
v=freq*arc_length;                      %sliding speed [m/s]
p_max=eta*load./(d.*L_min);             %projected pressure
```

```
p_min=eta*load./(d.*L_max);
p_avg=eta*load./(d.^2);

figure(1)
plot(d,p_min,'r'), xlabel('Shaft diameter [mm]'), ylabel('Projected presure [MPa]
grid on
hold on
plot(d,p_avg,'g')
hold on
plot(d,p_max,'b')
plot(d,Rm,'k')
plot(d,Rm+66,'k')          %additional example compressive strength from literatu
plot(d,Rm+114,'k')         %additional compressive strength from literature
legend('Bearing length=1.25*D','Bearing Length=D','Bearing length=0.75*D','PTFE c
figure(2)
plot(d,DN), xlabel('Shaft diameter [mm]'), ylabel('Bore diameter x rpm')
grid on
%%
%Bearing types evaluated as Wear, Corrosion, Load, Scalability, Lubrication, Clea
n=1.0;
neg=1.1;
nn=1.2;
%       Wear  Corr   Load  Scal   Lub    Maint
Type1=[0.5^nn 0.7^nn 0.5^neg 0.9^neg 0.6^nn 0.5^nn]; %Seawater lubricated polymer
Type2=[0.1^nn 0.7^neg 0.5^neg 0.9^neg 0.3^nn 0.2^neg]; %Dry, sealed polymer compo
Type3=[0.7^nn 0.7^neg 0.5^neg 0.9^neg 0.8^nn 0.5^neg]; %Sealed and greased (for l
Type4=[0.5^nn 0.6^nn 0.8^neg 0.9^neg 0.6^nn 0.4^nn]; %Seawater lubricated stainle
Type5=[0.6^nn 0.7^neg 0.9^neg 0.9^neg 0.5^nn 0.5^neg]; %Sealed Oil-lubricated cer
Type6=[0.6^nn 0.6^nn 0.9^neg 0.9^neg 0.5^nn 0.5^nn]; %Water lubricated ceramic sl
Type7=[0.1^nn 0.7^nn 0.7^neg 0.9^neg 0.5^nn 0.5^nn]; %Water lubricated bronze sli
Type8=[0.6^nn 0.7^neg 0.8^neg 0.8^neg 0.8^nn 0.6^neg]; %Sealed and greased (for l
Type9=[0.7^nn 0.7^neg 0.8^neg 0.8^neg 0.8^nn 0.6^neg]; %Sealed and greased (for l
Type10=[0.3^nn 0.6^nn 0.9^neg 0.8^neg 0.4^nn 0.2^nn];%Water lubricated ceramic ro
Type11=[0.4^nn 0.6^nn 0.85^neg 0.8^neg 0.4^nn 0.3^nn];%Water lubricated stainless

data2=[Type1' Type2' Type3' Type4' Type5' Type6' Type7' Type8' Type9' Type10' Typ
eval2=mean(data2);
figure(3)
Cell2{1}={'Type 1','Type 2','Type 3','Type 4','Type 5','Type 6','Type 7','Type 8'
x2=[1:1:11];
y2=[eval2];

boxplot(data2)

set(gca, 'XTick',1:11, 'XTickLabel',Cell2{1}, 'TickLabelInterpreter','none')
set(gca, 'XLim',[0 12])
```

```
set(gca, 'fontsize',12)
ylim([0 1])
ylabel('Rating 0-1')
xlabel('Bearing Type')
```

C. Rated bearings

The given rating and the calculated weighted rating for each design parameter shown in table below. References as background to the rating given in the rightmost column.

Table C.1: Rating model

	Wear	Corrosion	Load	Scalability	Lubrication	Cleaning	References
Type1	R=0.5 I=1.2 R^I=0.44	R=0.7 I=1.2 R^I=0.65	R=0.5 I=1.1 R^I=0.47	R=0.9 I=1.1 R^I=0.89	R=0.6 I=1.2 R^I=0.65	R=0.5 I=1.2 R^I=0.44	[8, 9, 22, 28, 29, 40]
Type2	R=0.1 I=1.2 R^I=0.06	R=0.7 I=1.1 R^I=0.68	R=0.5 I=1.1 R^I=0.47	R=0.9 I=1.1 R^I=0.89	R=0.3 I=1.2 R^I=0.24	R=0.2 I=1.1 R^I=0.17	[6, 8, 19, 39]
Type3	R=0.7 I=1.2 R^I=0.65	R=0.7 I=1.1 R^I=0.68	R=0.5 I=1.1 R^I=0.47	R=0.8 I=1.1 R^I=0.89	R=0.8 I=1.2 R^I=0.77	R=0.5 I=1.1 R^I=0.47	[8, 28, 30, 31]
Type4	R=0.5 I=1.2 R^I=0.65	R=0.6 I=1.2 R^I=0.54	R=0.85 I=1.1 R^I=0.84	R=0.9 I=1.1 R^I=0.89	R=0.6 I=1.2 R^I=0.65	R=0.4 I=1.2 R^I=0.44	[6, 17, 19, 20, 27]
Type5	R=0.6 I=1.2 R^I=0.54	R=0.7 I=1.1 R^I=0.68	R=0.95 I=1.1 R^I=0.95	R=0.9 I=1.1 R^I=0.89	R=0.7 I=1.2 R^I=0.54	R=0.5 I=1.1 R^I=0.37	[6, 17, 19, 37]
Type6	R=0.6 I=1.2 R^I=0.06	R=0.6 I=1.2 R^I=0.54	R=0.95 I=1.1 R^I=0.95	R=0.9 I=1.1 R^I=0.89	R=0.5 I=1.2 R^I=0.65	R=0.5 I=1.2 R^I=0.24	[6, 19, 41, 42]
Type7	R=0.1 I=1.2 R^I=0.06	R=0.7 I=1.2 R^I=0.65	R=0.7 I=1.1 R^I=0.68	R=0.9 I=1.1 R^I=0.89	R=0.5 I=1.2 R^I=0.65	R=0.5 I=1.2 R^I=0.54	[6, 17, 43, 44]
Type8	R=0.6 I=1.2 R^I=0.54	R=0.7 I=1.1 R^I=0.68	R=0.8 I=1.1 R^I=0.89	R=0.85 I=1.1 R^I=0.78	R=0.8 I=1.2 R^I=0.77	R=0.6 I=1.1 R^I=0.57	[6, 32, 34, 45]
Type9	R=0.7 I=1.2 R^I=0.65	R=0.7 I=1.1 R^I=0.68	R=0.8 I=1.1 R^I=0.84	R=0.8 I=1.1 R^I=0.78	R=0.8 I=1.2 R^I=0.77	R=0.6 I=1.1 R^I=0.57	[2, 6, 17, 27, 32, 34–36]
Type10	R=0.3 I=1.2 R^I=0.24	R=0.6 I=1.2 R^I=0.54	R=0.9 I=1.1 R^I=0.89	R=0.8 I=1.1 R^I=0.78	R=0.5 I=1.2 R^I=0.33	R=0.2 I=1.2 R^I=0.15	[6, 19, 45, 46]
Type11	R=0.5 I=1.2 R^I=0.44	R=0.6 I=1.2 R^I=0.54	R=0.85 I=1.1 R^I=0.84	R=0.8 I=1.1 R^I=0.78	R=0.5 I=1.2 R^I=0.33	R=0.3 I=1.2 R^I=0.24	[6, 19, 27, 32, 47]

D. Boxplot values

Table D.1: Boxplot values for each bearing type.

	Range	Mean	Median	Q1	Q3
Type 1	0.46	0.57	0.5	0.44	0.65
Type 2	0.83	0.42	0.35	0.17	0.68
Type 3	0.42	0.65	0.66	0.47	0.78
Type 4	0.56	0.59	0.54	0.44	0.78
Type 5	0.46	0.65	0.61	0.47	0.89
Type 6	0.46	0.62	0.54	0.44	0.89
Type 7	0.83	0.53	0.54	0.44	0.68
Type 8	0.24	0.69	0.72	0.57	0.78
Type 9	0.21	0.70	0.72	0.65	0.78
Type 10	0.75	0.49	0.44	0.24	0.78
Type 11	0.60	0.51	0.44	0.33	0.78