Test rig for submerged transmissions in wave energy converters as a development tool for dynamic sealing systems

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Abstract— **A submerged transmission, fitted with a dynamic sealing system, in a wave energy converter (WEC) serves the purpose of transmitting the force, absorbed by a wave activated body, to an encapsulated power take-off (PTO) system, while preventing seawater from entering the capsule. Dry generator operation is generally a prerequisite for attaining long technical service life. Little attention seems to be devoted in publications to the study of dynamic sealing systems in WECs, and to test rigs for experimental verification and/or evaluation of the ability/performance of existing dynamic sealing systems in a controlled laboratory environment. This paper begins by presenting some of our earlier research within the focus area of dynamic sealing systems, incl. design considerations and typical operating conditions. This part also presents the 1st laboratory test rig, used for verifying the sealing ability of the piston rod mechanical lead-through design in the 1st and 2nd full-scale experimental WEC prototype from Uppsala University. In 2021 project DynSSWE (Dynamic Sealing Systems for Wave Energy) was initiated. Drawing from experience, the project includes development of a new test rig, representing a tool for further development of dynamic sealing systems. This paper introduces steps in the design and development process of that new test rig, enabling accelerated long-term test runs with a setup of multiple piston rod specimens. The test specimens' will be surface treated differently with the aim of improving the prospects of a long maintenance free service life. Since the new test rig is in the design stage, seal testing results are not yet reported. The presented work is funded by the Swedish energy agency with the aim of improving subsystem performance in wave energy devices.**

Keywords—**Wave energy, test rig development, dynamic sealing system.**

I. Introduction

A. *Submerged transmission systems in WECs*

The performance of a reciprocating submerged linear transmission system attached to an encapsulated linear generator and its ability to seal off corrosive seawater, while transmitting the absorbed axial mechanical force from the waves into a wave energy converter (WEC), depends to a large extent on the mechanical behaviour of the transmission system. The system must be able to transmit the axial force while inflicting as little sideway force onto the sealing system as possible. The parts are subjected to a pulsating force ranging from no load up to several hundred kN or more during offshore operation [1]. Different solutions exist to reduce side forces acting on a sealing system, in order for wear to remain low. We have selected to exemplify this by referring to experiments conducted by Uppsala University.

Figure 1 illustrates the 2nd full-scale experimental WEC (L2) invented, built, tested and verified in sea trials by Uppsala University at the Lysekil Research Site (LRS) in 2009 [2 - 5]. A submerged piston rod mechanical lead-through transmission relays the axial force from the buoy, via a line, to the translator and seals off seawater from entering the generator capsule. A funnel at the top of the superstructure limits the extent of piston rod motion, i.e. tilting and sideways translation. A flexible attachment of the seal housing reduces the remaining side forces acting on the guiding elements in the dynamic sealing system. If the seal housing is not allowed to move elastically, side forces may become too high, and increase wear on the sealing system components leading to loss of sealing effect.

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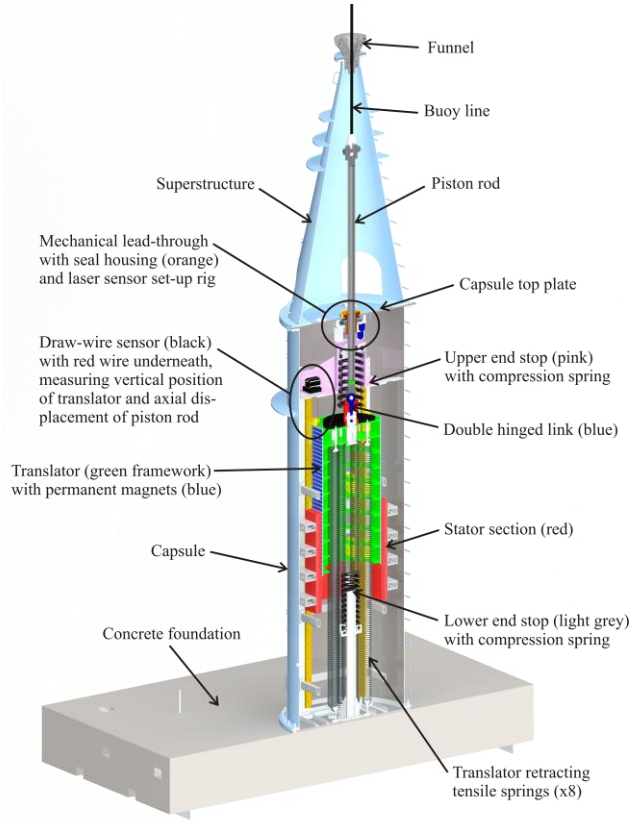

Figure 1. 3D rendering of the 2nd full-scale experimental WEC (L2) from Uppsala University, incl. some of the measurement systems, verified in sea trials at the Lysekil Research Site (LRS) in 2009. [2, 3]

Another important aspect affecting the sealing system is the pressure asserted by the sealed off medium, in this case seawater. Seawater pressure depends on sea depth. Most WECs would, however, probably be located in reasonably shallow waters, i.e. up to approx. 100 meters depth. If the capsule in fig. 1 is pressurized to match the mean outside water pressure, it would reduce the pressure differential on the sealing components. This is beneficial with regards to wear and would also reduce the amount of required material in the capsule, since the capsule has to withstand buckling from the absorbed side forces at the funnel, which cause bending on the outside WEC structure [5].

Understanding the motion pattern of the submerged transmission is a good starting point for reducing wear on the sealing system components. Wear is dependent on the sliding velocity and temperature at the interface between the sealing system components and the piston rod running surface, among other things. Lubrication and quality of the seawater, with regard to particles and bio-fouling, also affect the sealing system. Conditions at sea are difficult to simulate in a laboratory environment, so testing in actual sea conditions with actual forces acting on the system is valuable and important for developers, as well as rare.

Wear inside of bearings in wind power generators is often the cause of misalignment in the drive train, which gives rise to abnormal loading and accelerated wear [6]. An unbalanced magnetic pull in the generator, due to an asymmetric air gap, can cause vibrations, which further increases wear. Similar vibrations from misalignment and other sources of vibration in a WEC may also affect wear in a dynamic sealing system in a submerged transmission, and this is important to avoid as much as possible [7].

The axial force transmission in the linear reciprocating power take off (PTO) system of a WEC may also consist of another design solution other than a piston rod moving through a flexibly attached seal housing. It may be a piston head moving through a cylinder bore, or a seal off steel wire inside a rubber bellow moving with the stroke length of the WEC. These and other solutions can be found in hydraulic pumps, such as in construction-, agricultural-, mining-, and offshore machinery. These systems can work with very high pressures (several hundred bars), which generally put higher demands on the dynamic sealing system, since they may be operating under even worse conditions than what is to be encountered in the ocean.

A technology to draw experience from in the particular case of a direct drive transmission in a WEC, is the low pressure water hydraulics technology (LPWH) [8]. The drawback is that LPWH uses tap water as a pressure medium. Another obstacle is the fact that it takes time to fully verify a technology that is aimed to seal and to be maintenance free for many years, even though accelerated tests may be performed. Fortunately, the mechanisms and theories regarding sealing technology and tribology, are verified and considered well known [8]. A sealing system's life time, operating in a certain environment under certain conditions, still has to be investigated for each individual case. Some examples of sealed transmissions, hydraulics and dynamic sealing systems for other machines and even WECs can be found in [8, 10 – 12].

B. *Dynamic sealing system technology*

A dynamic sealing system seals against a moving surface, as compared to a static seal, like a clamped gasket or an O-ring. A dynamic sealing system should have low friction and good shape elasticity to ensure correct function. The system is expected to be compatible with the media at relevant temperatures, and have high resistance to mechanical damage. Different specific requirements in numerous applications have resulted in the development of different sealing designs. A dynamic sealing system contains multiple types of components with different purpose. A reciprocating system like the one sealing off seawater in a WEC uses so-called hydraulic seals, with at least a primary and a secondary sealing. Guiding elements guide the piston rod through the seal housing (or vice versa). One should follow the sideway motion of the other instead of working against each other, thus elevating the side forces. Wipers and scrapers may be added to protect the sealing components from particles, if necessary [12].

To reduce friction and wear, the running surface of the moving piston rod should be separated from the sealing components by a lubricating film. The formation of the lubricating film is influenced by the design of the sealing edge (or tip), see fig. 2. The operating seawater pressure and the magnitude and direction of the relative motion, as well the structure of the counter surface (wettability) and the properties of the medium (viscosity) contribute to the outcome [12]. The pressure curve beneath the sealing edge, seen in fig. 2, should be steep in the direction for which the sealing is supposed to seal, and a little bit flatter in the other direction. In this way a thin film of lubricant is left on the piston rod surface after the return stroke. Lubrication is generally favoured by low water pressure, high stroke velocity and a long stroke, compared to high water pressure, lower stroke velocity and a short stroke. Low velocity will reduce the hydrodynamic effect of the lubrication film to move in under the tip. In a point absorbing WEC with a linear generator, change in the reciprocating motion occurs at the outer end stops. These turning points represent instances of the highest friction,

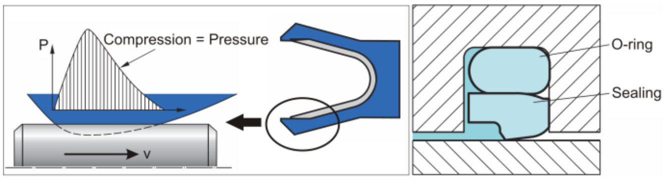

Figure 2. Left: Compression curve at the tip of a piston rod U-cup stainless steel spring sealing. Right: Two component sealing with an O-ring as the pre-pressurizing component. [2]

i.e. when so-called static friction (or dry solid-body friction) may occur for a short instance.

Heat development at the sealing tip (edge) during operation can generally be a problem depending on the situation. A rule of thumb is to allow approx. 20 % higher temperature at the sealing tip interface compared to the overall system temperature [10]. Although velocity is a limiting factor, it is not as sharply defined as temperature and pressure, since increased velocity can be offset by increased cooling of the sliding faces. The conditions near the seabed are very favourable with regard to temperature, 0-4 °C depending on time of year, up to approx. 20 °C at shallower depths during summer time.

A sealing component is referred to as "leaky" if the medium being sealed off is visible from the outside in the form of dripping leakage. Causes of measurable leakage may be attributed to wear on the seals or expansion of the housing on the static side, assuming tolerances with regard to the rules of design of the surfaces have been accounted for; cracks in the materials; increasing hardness of sealing material due to operating conditions or media; reduced hardness due to swelling with consequences on increased wear; corrosion of the piston rod; lubricant loss; aging depending on choice of material; vibrations resulting in the sealing lip being unable to follow the counter surface; continuous ingress of dirt at the sealing lip resulting in premature wear; damage to the sealing edge or piston rod counter surface during transport, handling or assembly, among other things [2].

C. *Marine bio-fouling*

Different parts of the world show different salinity levels as well as different bio-fouling, which may affect the choice of materials and the amount of marine grease needed to be applied as lubricant for different sites.

Natural seawater contains living organisms, which very quickly form a bio-film with van der Waals forces on stainless steel [13]. This bio-film increases the risk of pitting and crevice corrosion. The activity of the bio-film is temperature-related, but since the different organisms are adapted to the natural temperature of the water, their activity varies between different seas around the world. The seawater is most aggressive at 25 - 30 °C and above, which occurs in the so-called surface splash zone. Lower depth, lower sun radiation, lower temperature and lower salinity reduces the activity. In Scandinavia, depths greater than 65 meters exhibit little but slimy bacteria [14].

In other places bio-fouling may progress beyond the bio-film. The bio-film includes bacteria, yeasts, unicellular algae and protozoa. The presence of adhesives secreted from the organisms along with the roughness of irregular microbial colonies help to trap more particles and organisms [15]. Thereon follows a transition from bio-film to a more complex community, such as algal spores, barnacle cyprids, marine fungi and protozoa. The final stage involves settlement and growth of larger marine vertebrates (macro organisms), commonly denoted as macrofoulers composed of organisms that can secrete hard calcium carbonate tubes, shells or skeleton (i.e. barnacles, mussels, tubeworms, bryozoans and corals) or soft organisms (i.e. algae, hydroids, sponges and ascidians). As soon as the bio-film is converted to hard calcareous material, physically attached to the surface, it becomes potentially damaging for the dynamic sealing system.

Different types of bio-fouling may possibly be repelled or inhibited in different ways and at different stages, either mechanically (by including a scraper or wiper in the dynamic sealing system), chemically, biologically, through surface physics and even electrically, in order to reduce or even eliminate bio-fouling [16]. However, these methods may, to a varying degree, be difficult to implement in dynamic sealing systems. To the authors' knowledge some work may still remain within this field of research.

II. Prior experimental Test rig

The submerged piston rod mechanical lead-through transmission used in the 1st and 2nd experimental WEC prototype (L1 and L2) by Uppsala University, constituted a unique solution designed to meet the requirements of the WEC. Before L1 a similar design solution for a WEC could not be found in literature. Thus, the design had not been verified. Oscillating motion with angular tilting combined with pressurized saltwater required testing prior to launch of L1. The dynamic sealing system in the mechanical lead-through was qualitatively evaluated in a test rig to make sure that the solution prevented seawater from potentially leaking into the WEC generator capsule. A custom-made full-scale laboratory test rig, illustrated in fig. 3, was designed, built and implemented by E. Strömstedt (co-author of this paper) to investigate the dynamic sealing ability of the submerged transmission by simulating WEC motion in pressurized underwater conditions [2].

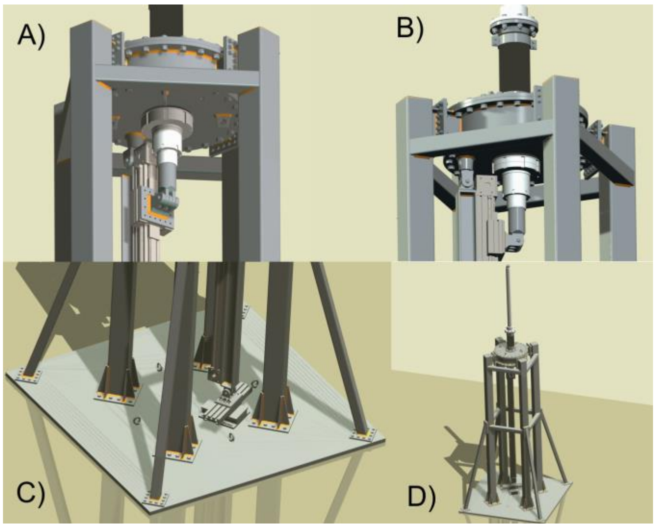

Figure 3. 3D rendering of the first experimental test rig designed for full-scale performance evaluation of the submerged transmission in WEC L1, while simulating underwater conditions in a laboratory. A) and B) Two views of the top structure with pressure vessel, linear unit and piston rod mechanical lead-through housing a dynamic sealing system. C) Layout on top of test rig bottom plate, incl. linear unit attached to coordinate table. D) Overall assembly view of test rig. [2]

A very robust framework structure was constructed from parts already in-house. At the top of the framework a cylindrical pressure vessel is bolted to the four corner pillars. The pressure vessel is dimensioned according to national pressure vessel directives for operating pressures of up to 3.5 bars in a volume of 1 m^3. This simulates the water pressure at 25 m depth, equalling the depth at the LRS, where L1 was to be tested. The steel framework structure provided a solid support for future testing with larger vessels, housing several cubic meters of water, enclosing entire full-scale stroke lengths and longer bellow solutions.

The seal housing is mounted to the bottom plate of the pressure vessel in the same way as it is mounted to the capsule top plate in WEC L1 and L2, used the exact same solution. For more information concerning the design of the dynamic sealing system in L2 see [2, 3 and 5].

The piston rod is attached with a clevis joint to a sleigh that moves on rails and set in motion by a belt driven linear module mounted to an H-beam. The H-beam is hinged around a horizontal axis at the top and at around the same axis at the bottom. At the bottom the H-beam is connected to a coordinate table. The table can be displaced a certain horizontal distance perpendicular to the H-beam hinge axes. The hinged H-beam is not fixated to the pressure vessel at the top end. Instead a wedged cylinder on top of the H-beam sticks into a slotted bore welded to the vessel, see image B in fig. 3. The wedged cylinder can slide up and down inside the bore, but not rotate due to the wedge. The one degree of freedom (DOF) for the cylinder to slide up and down allows the H-beam to slide down so that the bottom end can be moved sideways with the coordinate table. This enables the H-beam and linear module to be tilted at a selected angle to the vertical axis, enabling the piston rod to operate with varying angular tilts as it moves up and down. When the piston rod reaches the upper end stop, it will be standing in a vertical position. At the lower end stop, it may reach a maximum tilt angle of 1.25° depending on the settings of the coordinate table. The varying tilt angle simulates the expected motion of the piston rod in the WEC [2, 5].

The linear module is driven by a servo-motor, BSM90N-3150BA from Baltor. It is supplied with a gear head and a mechanical break. The linear movement is controlled with NextMove ESB Motion Controller from Baltor, a motion control system operated through a workbench interface using a Visual Basic input configuration for handling sinus waves and real wave data, as well as setting time periods, amplitudes and velocities.

The stroke length of the linear module (2.25 m) is slightly longer than the permissible mechanically stroke length in the test rig. Therefore, safety limits are guarded by inductive sensors/switches sensing the presence of a steel bar attached to the aluminium sleigh, which drives the piston rod up and down. If the sleigh reaches the upper or lower end of the permissible stroke (1.3 m) the sensor sends a signal to the control system to engage the mechanical break and to cut the power supply. The system may then be reset, restarted and repositioned using a third inductive sensor/switch located inside the permissible stroke length.

The pressure vessel is 25 cm high and is half filled with seawater. The seawater for the conducted experiment was brought in from the LRS and contained the appropriate salinity, bacteria, algae or defined particles. The pressure vessel has attachments for water inlet and outlet, with an impeller pumping water from an external bucket. However, the test rig did not provide a circulating water system which would simulate conditions at the LRS ever further.

Attached to the top centre of the vessel is a large fiber-reinforced rubber hose. The hose sticks up half a meter and is made out of a material strong enough to withstand the inside pressure. At the top of the hose there is a pneumatic sealing system sealing off around the piston rod enabling the pressure to be maintained inside the vessel. The flexible hose is chosen for its minimum influence on the motion of the piston rod, which should be guided only by the seal housing at the bottom plate of the pressure vessel.

The vessel has an air (or nitrogen) pressure inlet/outlet. A regulator system is attached to the inlet/outlet and to the local air pressure system at the Ångstrom Laboratory for controlled elevation of gas pressure. A security valve is attached to the top of the pressure vessel for releasing pressures exceeding 4.5 bars, which is the allowed limit. An underwater night-view camera with its own lighting is set-up inside the pressure vessel to monitor the experiment under water from inside the pressure vessel, as shown in fig. 4. Images are transmitted via cable through the top plate and visible on computer screen at the control station.

The purpose of the laboratory experiments was to verify the functional abilities of the piston rod mechanical lead-through and the dynamic sealing system with regard to the significance of operational behaviour and non-leakage during the awaiting sea trials. The wave motion was simulated by approximating the motion with a sinus curve. However, the test rig may be operated with real wave data from, for example, a wave measuring buoy.

The mounted piston rod was mechanically driven up and down through the seal housing at velocities of up to 0.67 m/s (nominal velocity for the WEC) with a stroke length of 1.3 m and period of approx. 6 s, as shown in fig. 5. No leakage was observed after 4 hours of testing with 2 bars inside over-pressurized. The same experiment was conducted with non-pressurized water. The set-up was run with both a strictly straight vertical motion throughout the entire stroke, and with the piston rod moving from a vertical position into a 0.5° tilted angle, and back into a vertical position. Figure 4 shows images from the testing sessions, before the submerged transmission was installed in L1. The inner framework of L1 can be seen in the background behind the test rig in image B of fig. 4.

The experimental results from the test rig indicated good sealing functionality with no observable leakage.

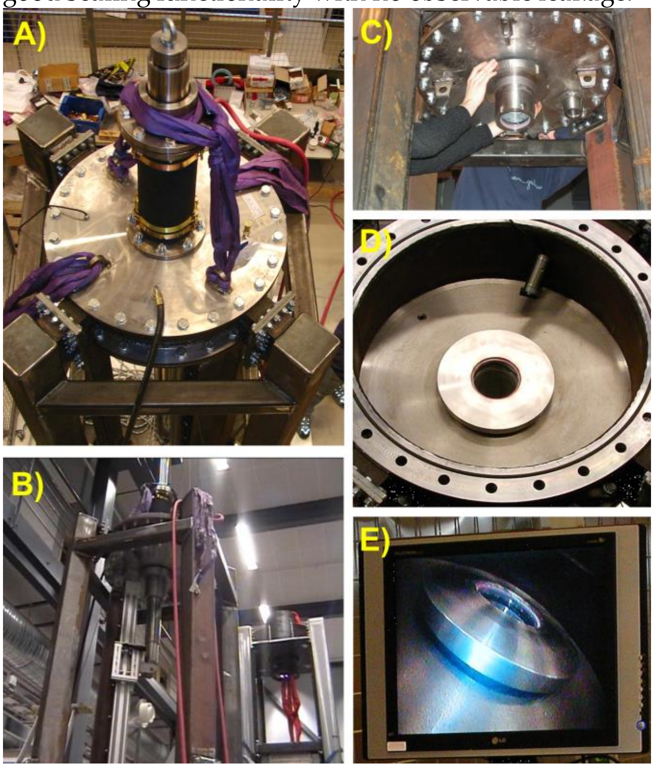

Figure 4. A) and B) The first laboratory test rig during operation with the piston rod mechanical lead-through later installed in WEC L1. The WEC L1 inner framework structure is in the background of image B. C) Mounting of seal housing in the test rig. D) Display of the inside of the pressure vessel with the seal housing and an underwater (UW) camera. E) UW camera image on screen at nearby control station. [2]

Life-time expectancy of the dynamic sealing system was still unknown, and at the time subject to further research.

Figure 5 shows the oscillating velocity curve (green) for the piston rod motion during testing. The demanded AC (DAC) by the servo-motor is also plotted (blue) as a percentage of the peak RMS current (16 A). The plot shows increased DAC on the piston upstroke due to the gravity force, inertia from accelerating the mass of the moving parts and friction inside the sealing system.

The test rig is designed with a feedback resolver connection in order to retrieve data from the motor. The DAC by the servo-motor and the velocity of the stroke ($\dot{z}$)

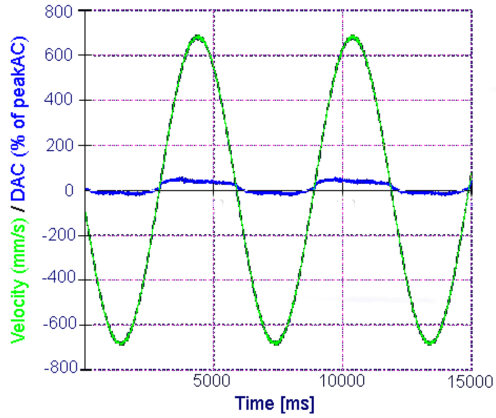

Figure 5. Captured image from the test rig control system showing the oscillating velocity of the piston rod strokes, in green, peaking at 0.67 m/s in both directions for a stroke lengths of 1.3 m. Demanded AC (DAC) in amps as a percentage of the peak RMS current (16 A) in the servo-motor, is shown in the blue curve. [2]

may be used to estimate the friction force in the experimental set-up (F_{FR}) by also knowing the total mass of the moving parts, i.e. piston rod, sleigh and fixtures, driven by the linear module and the torque of the servo-motor at peak AC. Equation 1 states the mathematical relationship, according to Newton's second law of motion,

$$m_{\text{moving parts}} \cdot \ddot{z} = \left(\frac{\tau_{\text{servomotor}}}{r_{\text{linear module}}}\right) - (m_{\text{moving parts}} \cdot g) - F_{FR} \qquad \text{(eq. 1)}$$

where ($r_{\text{linear module}}$) is the radius of the cogwheel for the belt driving the sleigh on the linear module and ($\tau_{\text{servomotor}}$) is the torque achieved with the momentary DAC. However, F_{FR} includes the friction in the pneumatic seal at the top of the test rig, as well as the friction force in the dynamic sealing system intended for the WEC.

III. THE DYNSSWE PROJECT

A. *The DynSSWE project main objective*

A new project initiated in 2021, project DynSSWE (Dynamic Sealing Systems for Wave Energy), financed by the Swedish Energy Agency, will provide new knowledge of common value for the entire Swedish wave energy industry with regard to generic aspects on specific dynamic sealing systems in WECs, as well as provide insight to other parties in the national value chain, especially within sealing systems, materials science and surface treatment.

The project will realize and implement a new test rig design for evaluating dynamic sealing systems, among other things. Right now, this is work in progress, but a brief introduction of the development methodology is given in section IV.

B. Background and incentive for project DynSSWE

A number of Swedish WEC developers are currently investigating the possibilities to extract electric energy from ocean waves. All established Swedish WEC concepts rely on the performance of dynamic sealing systems operating with linear motion. The technologies are briefly presented in the following webpages, where the images indicate their respective sealing interfaces:

- Corpower Ocean ((http://www.corpowerocean.com/technology/#corpowerConcept)
- Seabased (https://www.seabased.com/the-technology)
- Waves4power (https://www.waves4power.com/waves4power-the-solution/)
- Ocean Harvesting (https://www.oceanharvesting.com/infinitywec-technology/)
- NoviOcean (https://noviocean.energy/concept-general/#technology)
- Eco Wave Power (https://www.ecowavepower.com/our-technology/how-it-works/)

Comparing the strategies of these projects, there are very different technical solutions under development. Each technology brings a new set of questions to be answered. One thing most of these projects have in common is the challenge of developing mechanically durable subsystems that can sustain millions of cyclical sequences of varying dynamic, and potentially very high, mechanical loads in the harsh environment at sea. A submerged WEC may be constructed for dry or flooded generator operation. Dry running means sealing off the generator from the corrosive seawater. Sealing off the generator enables the use of cheaper and less corrosion resistant materials, which suppresses the need for coating the generator parts inside the capsule. Commercially available coated permanent magnets have unfortunately shown to corrode rapidly in seawater, and there is also always the risk for electrical components short-circuiting in contact with seawater.

Sustainability of the sealing function in a submerged transmission system can be keynote to the economic viability of a wave power plant. I could even be more important than the conversion efficiency, especially if it is an offshore installation requiring expensive maintenance operations. Offshore installations are generally costlier to maintain since they require large sea vessels and divers to work on and/or pick up the device for transportation to shore. Installing a WEC generator on the seabed may protect it from extreme forces of waves at the surface during stormy weather, as compared to exposed surface-floating devices and onshore installations in break water areas. On the other hand, they may become less accessible.

So far marine biological studies of WEC technology indicate that submerged offshore installations may improve the marine environment by creating artificial reefs for the recuperation and protection of the flora and fauna in the ocean, but the flip side to that is that bio-fouling may attach itself to sensitive surfaces operating in contact with dynamic sealing systems. These systems represent critical parts for attaining a long technical service life, without catastrophic failure, costly maintenance and the connected interruption of the power generation.

Several of the Swedish WEC developers have very limited experience from actual sea trials. At Uppsala University we have over a decade of experience from several unique sets of offshore sea trials and of full-scale wave energy converter systems with dynamic sealing systems in linear reciprocal motion with our various industrial partners. We also have long term established contacts with world market leaders in sealing technology such as Trelleborg Sealing Solutions, Freudenberg Simrit, Klüber Lubrication, and a host of suppliers for machine processing, coating and for applying various surface treatments.

IV. Test rig development methodology

Building a test rig for simulating ocean wave movements and sea water environment consists of solving many different tasks in order to complete a usable test rig for its purposes. By structuring the workflow accordingly, it is easier to plan, execute, and follow up on tasks in order to successfully finish the project. The project design phase is carried out by following the work flow of Ulrich and Eppinger [17]. It is started with identifying the problem and what is to be solved and/or examined with the planned test rig, followed by a brief design overview with functions and deliverables in order to construct a time plan. To design the test rig in more detail the specifications are listed, which further makes the conceptual design phase more concertized. As the conceptual design phase proceeds, it is clearer on what parts are needed for the build, and the requirements of those. For a first verification, calculations and simulations are used to verify the structural integrity of the structure to meet the mechanical specifications of the test rig. Before delivery, the test rig has to be assembled and all functions need to be verified to ensure that test rig meets the specifications and fulfils all the objectives and functional demands.

A. Test rig objective and functional demands

The purpose of the test rig is to simulate a piston rod mechanical lead-through system designed to transfer the axial force from a wave activated body into an encapsulated linear generator, while sealing off seawater from entering the capsule. The mechanical lead-through houses a dynamic sealing system adapted for WEC operation in terms of a linear reciprocating motion in an ocean-like environment with water containing high salinity, and possibly relevant particles and marine organisms.

The objective is to run scaled (around 1:4) tests cycles with different combinations of sealing systems and piston rod surface treatments to find the best combination in order to improve the general lifetime of the sealing system. A test rig corresponding to 1:4 scale gives a stroke length of around 0.5 m by assuming a wave height of about 2 m [18], [19]. Since the expected lifetime of a WEC, in general terms, is around 20 years [20], a test rig cycle should be accelerated in order to improve chances of creating enough observable wear on the piston rod running surface, and sealing components, to be able to analyse and compare the performance in the tribosystem using micro- and spectroscopy.

In order for the test rig to work as intended, some necessary main functional demands are listed below:

- Drive a setup of piston rods through corresponding seal housings, fitted with selected dynamic sealing systems, with a linear stroke.
- Ability to tilt piston rods in stroke to simulate possible motion patterns in point absorbing WECs.
- Flexibly mount seal housings to water vessel, i.e. water encasing structure, enabling a compliant motion with low side forces.
- Achieve intended interaction between seal housing, mounting solution and water encasing structure.
- Achieve intended interaction between piston rod and components in the dynamic sealing systems.
- Achieve intended transfer film on running surfaces at points of interaction.
- Simulate wave motion either with fabricated or real wave movement data.
- Simulate ocean water environment with salinity (either fabricated or real ocean water) and possibly with abrasive particles.
- Make real time measurements of water leakage.
- Make real time temperature measurements, such as of water and ambient temperature.
- Measure displacement of piston rod in five degrees of freedom (DOF).
- Measure displacement of seal housing in five DOF.
- Calculate actual piston rod movement from linear unit position feedback and tilt angle of linear unit.
- Possibility to change cycle parameters, such as cycle length, frequency, and stroke length.
- Possibility to survey and control operation locally and remotely.
- Store measurement data both locally and remotely.

Since the main purpose of the test rig is to evaluate and improve (i.e. reduce) wear between the dynamic sealing components and the piston rod, it is important to create the environment needed for the interactions to happen. Allowing for a reciprocating linear motion with the same maximum stroke velocity as expected in a corresponding WEC, but with a higher frequency will lead to higher abrasive and adhesive wear. The tilt of the piston rod relative to the seal housing will put increase the perpendicular faced force, relative to the direction of movement, on the components in the sealing system inside the seal housing, particularly on the guiding elements. This will lead to higher adhesive wear and velocity up the interaction between the running surface of the piston rod and the components in the seal housing. To gain relatable results regarding wear between sealing component and piston rod surface, an important aspect is to mimic the piston rod movement relative to the sealing components as it is in reality. This is achieved by either using fabricated data, like an ideal sinusoidal moving pattern, or by using real wave buoy data. The ocean environment plays a big part in the wear rate between the tribosystem interfaces. This is why it is important to include this environment (as appropriately as possible) into the test rig and to keep it in mind when examining the wear between the surfaces. In order to follow the wear process in real time, one option would be to measure the relative tilt angle between piston rod and seal housing in order to draw conclusions about the wear rate of the sealing system guide elements. [2]

B. *Planning*

The preliminary planning for this project was done once the concept and the purpose of the test rig was detailed enough to make an overall structure of test rig functions and deliverables. The functions of the test rig were mapped into a tree structure to more clearly see which functional demands needed to be implemented in to the test rig. Once the function breakdown structure was done it was time to create a delivery breakdown structure. Like the function breakdown structure, the delivery breakdown structure was created in a tree structure where each function was reflected in one or more deliveries. This was done in order to get better insight into what actually needed to be delivered to implement all the functions. When the two breakdown structures where created, a work breakdown structure was made translating all the deliveries in to one or more actions for the purpose of getting a better overview on tasks and actions needed to be done when designing the test rig. All the actions in the work breakdown structure where then time estimated and put in a PERT chart to create a Gantt chart.

C. *Technical specifications*

Ahead of starting the conceptual design phase, test rig technical specifications are listed. The specifications are supposed to be seen as a quantitative and measurable way of visioning what the performance and functionality of the test rig should be like [17]. The following list comprises some of the identified specifications for the design process of the test rig.

- Stroke length of at least 0.5 m.
- Maximum stroke velocity of at least 1.5 m/s.
- Possibility for simultaneous testing of five piston rods.
- Water tank capable of holding water long-term with a salinity of at least 35 ‰.
- Ability to tilt the linear unit at least 2.5°.
- Cycle length of at least 3 months.
- Maximum linear unit motion frequency of minimum 0.4 Hz.

In order to run the accelerated test cycles generically and as close to reality as possible, it is important to reassure that the specifications theoretically correspond to the accelerated environment (both water and motion) according to real wave data combined with the scaling laws of Froude [21]. With a scaling factor of 1:4 a suitable stroke length of around 0.5 m correspond to a wave height of 2 m. A maximum stroke velocity of 0.75 m/s would result in a stroke velocity of 1.5 m/s in a scaled environment. To enhance the interaction between the sealing system guide elements and the piston rod running surface, the ability to tilt the linear unit, according to fig. 7, with up to 2.5° would lead to an increased interaction between the surfaces. Regardless of how accelerated the test may be, there is still a need for the possibility to run tests for at least 3 months in order to make the wear of the piston rod and sealing elements more distinct. The option to have a stroke period faster than a real ocean wave is necessary to carry out the accelerated and scaled testing.

The technical specifications often change along the project and this project will not be an exception. As the design for the test rig is getting more detailed, more demands arise in order to ensure good operation and trustful results. For example, a linear unit driving the piston rods in a linear reciprocating motion have demands on tolerances regarding sideways motion and position that will be further investigated.

D. *Conceptual design*

The conceptual design gathers data from all previous steps in the project and renders that in a first design draft of the test rig. The conceptual design of the test rig consists of a rectangular shaped water tank at the top of the test rig, supported by a frame structure. On the bottom of the tank there are five holes where five mechanical lead-throughs are flexibly installed and fitted with the sealing systems. On each short side of the water tank, there is a linear unit with a bar across, connecting the two linear units, see fig. 6a-c below. Since the water tank is not designed to be pressurized, the walls will be constructed in a thicker plastic, or glass, material. This would be selected in order to clearly see the movement of the piston rods inside the water tank.

The five different piston rods are connected to the bar which allows for driving all piston rods at the same time. Each linear unit is connected to a coordinate table at the bottom to allow for slight shifting to make the piston rods work in a tilted "J"-like motion, see fig. 7. The piston rods are connected with a clevis joint coupling to the bar, which allows for rotation with one DOF, in order for the piston rods to follow the tilted motion from the lower sideways offset created by the coordinate table.

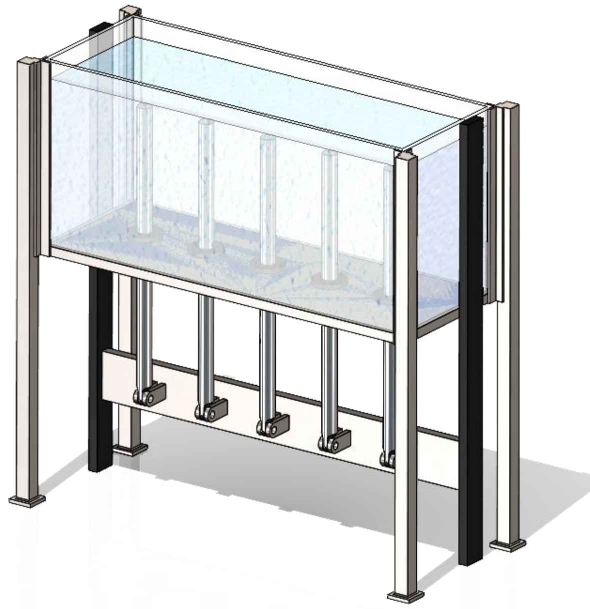

Fig. 6a. A 3D rendering of a conceptual design in Solidworks.

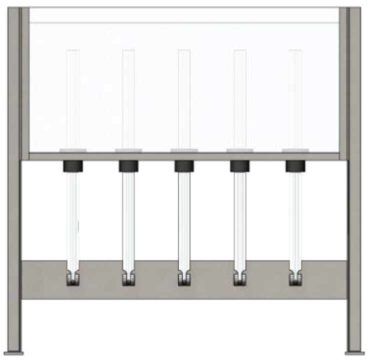

Figure 6b. A 3D rendering of the conceptual design in fig. 6a seen from the front angle.

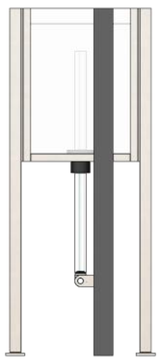

Figure 6c. A 3D rendering of the conceptual design in fig. 6a seen from the side angle.

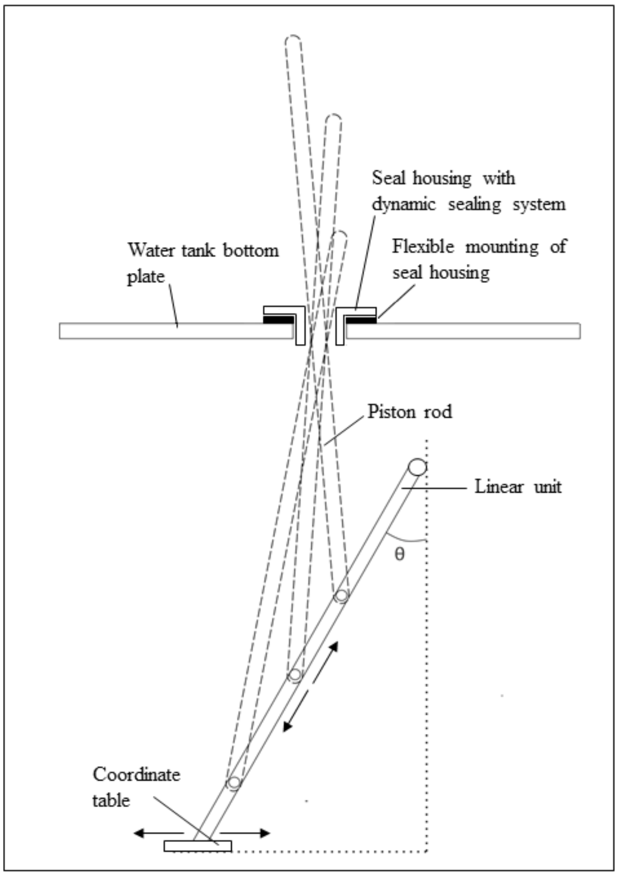

Figure 7. An illustration of the "J"-like piston rod motion in the conceptual design illustrated in fig. 6a, 6b and 6c.

E. *Parts selection, calculations, simulations and final design*

This is the current phase of the project where the next thing to do is to select all the parts for the test rig in order to make a more detailed design. Once all the parts are selected it is easier to make a final design, since all dimensions of all the parts and solutions are known. The final design will be modelled in a favourable 3D-modelling software like Solidworks®.

To comply with all technical specifications, calculations and simulations is necessary in order to make sure that the structural integrity is good enough for all the intended purposes.

F. *Ordering, assembly, programming and verification*

The next step is ordering all the parts. Once all the parts have arrived it is time to assemble the test rig. When the test rig is assembled, programming of the code for controlling the cycle sequence (duration, motion pattern etc.) for long-term testing and for controlling and logging of data with multiple measuring systems in the test rig will be conducted. The plan is to use LabVIEW software from National Instrument for this purpose. Verification of all functions and subsystems, as well as validation of the operation, with regards to the stated objectives of the test rig will finalize the development process.

V. Concluding remarks

Among other things, this paper describes the past test rig designed for pre-sea trial evaluation of the submerged piston rod mechanical lead-through transmission installed in the 1st and 2nd full-scale experimental WEC prototypes developed at Uppsala University and the purpose behind the test rig. Since the main objective of that test rig was focused on evaluating the interaction between the piston rod and dynamic sealing elements of that particular system, the authors are now developing a new test rig as a development tool for improving the dynamic sealing system design and performance in generic point absorbing WECs. With the ability to run up to five piston rods simultaneously in a scaled and accelerated environment with different surface treatment, the possibilities expand. Qualitative and quantitative test cycles will be easier and the output will provide more knowledge on potentially suitable running surfaces combined with contemporary state of the art sealing components, to provide longer operating service life for these submerged transmission systems. If possible, the project outcome may thereby eventually contribute to more economically viable WEC devices with reduced maintenance requirements relating to water leakage in these systems.

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