This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101006927.

Verification through Accelerated testing Leading to Improved wave energy Designs

Deliverable 3.2

Design and manufacturing report for the physical test rigs

Version 1.0

2023-02-15

Lead participant: CPO

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Executive Summary

This report is the second deliverable in WP3 – User Case #1: Testing of Dynamic Sealing Failure. Deliverable 3.2 covers the upgrades that were made to the seal test rig as part of CorPower's user case (User Case 1 – UC1) of the VALID project, both in term of hardware and software.

The first part of the test program (Machine Learning demonstration with advanced monitoring techniques) required minimal new hardware but some smart adjustments of valves and sensors, as well as a major rehaul of the seal rig software with better data labelling and storing.

The second part of the test program, during January-February 2023 required design, sourcing, and assembly of the first full-diameter rod and chamber in the seal rig. This setup is now physically assembled and under testing.

A design extension was created for water exposure in the seal test rig. This design will allow the monitoring of media exchange (oil/water) and guide the design of the ocean-facing seals and scrapers.

More upgrades might be needed along the test program (see D3.1 User case and methodology report for User Case 1 [1]) according to the previous results. These upgrades will be documented in the subsequent deliverables within WP3 or as updates of D3.2.

Project partner names

- RISE Research Institutes of Sweden AB
- Fundacion Tecnalia Research and Innovation
- Corpower Ocean AB
- RINA Consulting S.p.A.
- Biscay Marine Energy Platform SA
- IDOM Consulting, Engineering, Architecture, S.A.U.
- Aalborg University
- AVL List GMBH
- Wavepiston AS
- Delft University of Technology
- Aquatera Sustainability Ireland LTD
- Julia F. Chozas, Consulting Engineer
- Yavin Four Consultants, Unipessoal LDA
- Aquatera Atlantico
- Technical University of Denmark

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Figures

1 Introduction

This report describes the design and implementation of the upgrades carried out on the CorPower Ocean dynamic sealing test rig within WP3 – User Case #1: Testing of Dynamic Sealing Failure, Task 3.2 Design and manufacturing of the VALID project.

1.1 Project and Work Package background

The VALID project will develop a methodology for hybrid testing in the ocean energy sector, with the objectives of:

- Accelerating the physical testing process
- Aiding timely decision-making by early prediction or indication of failures
- Improving confidence in overall testing, especially regarding the reliability of data which is difficult to obtain without real ocean testing.

WP3 investigates CorPower Ocean's Wave Energy Converter (WEC) as a user case for the hybrid test methodology. Specific focus is placed on the WEC dynamic sealing systems which are critical components in the system and are subject to complex degradation processes that lead to hard-to-predict failure scenarios. More can be read about the user case and specific dynamic sealing systems in D3.1 [1].

1.2 Task aim

Task 3.2 has focused on the design and implementation of upgrades of the CorPower Ocean dynamic seal test rig. The test rig was originally developed as part of the Horizon 2020 (H2020) funded *WaveBoost* project [2] and is upgraded as part of the VALID project to enable implementation of the hybrid test methodology.

This task has involved:

- Investigation and planning of required upgrades
- Rod sample design, procurement, and integration
- Sealing setup design, procurement, and integration for seal rig and ocean deployments
- Reconfiguration of sensor setup on seal rig
- Design, procurement, and integration of a full-scale rod setup to enable evaluation of scaling effects. This has included work on:
    - Full-scale rod design & procurement
    - Sealing chamber design & procurement
    - Design, procurement, and integration of higher capacity load cells
- Design, procurement, and integration of a water-chamber setup to evaluate dynamic media separation.
- Software overhaul to enable more reliable data capture, and accurate data labelling from each sensor signal and test setup to allow detailed post-processing using e.g. machine learning algorithms for feature detection.

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1.3 Structure of report

This report is structured in the following way:

- Section 2 gives an overview of the test rig that was developed during the H2020 WaveBoost project.
- Section 3 describes the design of the upgrades, including a justification for each.
- Section 4 describes the implementation of the upgrades.
- Section 5 offers some remarks and conclusions on the upgrades in the context of the VALID project and with an eye to the future.

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2 Overview of existing test rig

The following section gives an overview of the dynamic sealing test rig that was developed by CorPower Ocean within the H2020 funded *WaveBoost* project. This test rig has been significantly upgraded and overhauled to enable the scope of work to be conducted in the VALID project. Sections 3 and 4 give a description of the design and implementation of these upgrades respectively.

2.1 Description of existing test rig

The seal test rig (Figure 1) is a universal high-speed reciprocating rig, that has been designed to test lifetime and performance of critical components for the next generations of CorPower's Wave Energy Converters (WECs).

It is equipped with:

- a crank-slider mechanism powered by an electric motor
- a hydraulic system, providing cooling and lubrication oil
- a high-pressure air supply
- a set of sensors to measure positions, speeds, forces, pressures, temperatures, and flows
- a central PLC (programmable logic controller) for the control, safety algorithms, data acquisition and conditions monitoring.

The actuator is composed of a crank-slider mechanism that provides a linear reciprocating motion. The crank wheel is powered by an electric motor spinning with a constant speed instruction. Due to its high inertia, the wheel acts as a flywheel, storing and releasing energy from and to the reciprocating slider. Thus, the variations of loading are not directly seen by the motor, and the electrical power supply is smoothened.

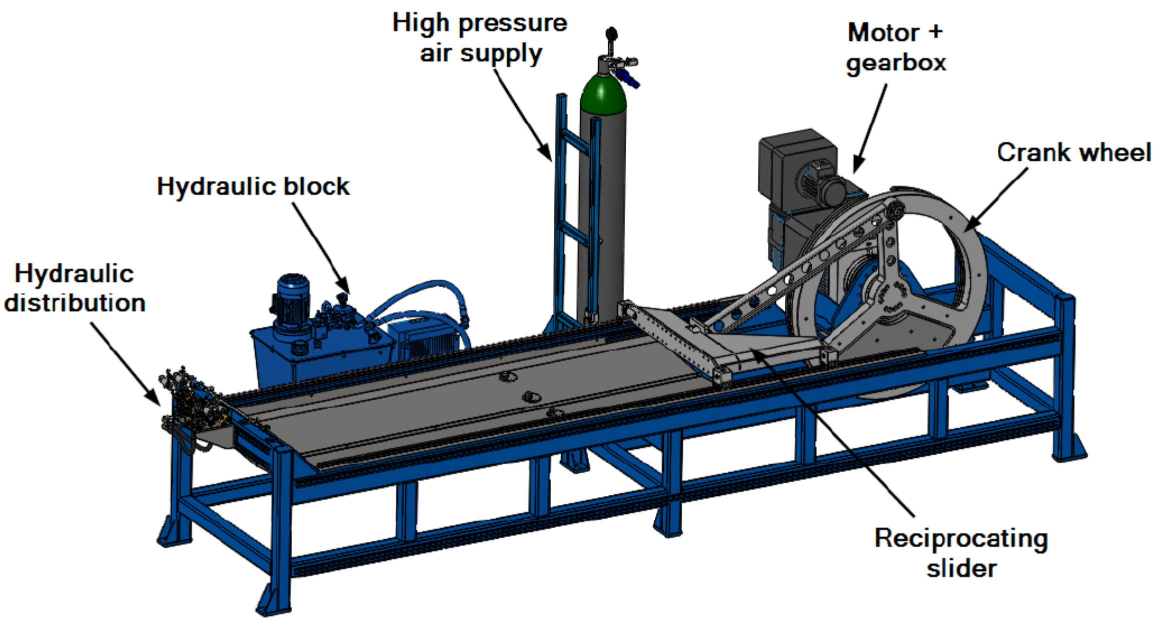

Figure 1: Existing dynamic sealing test rig.

3 Design of Upgrades

As part of the VALID project a campaign of testing was decided upon which required the upgrade of the dynamic seal test rig in terms of hardware and software. This section describes those upgrades.

3.1 Justification for upgrades

The test plan that was formulated in D3.1 [1] required an upgrade of the dynamic seal test rig.

The hardware upgrades included new experimental setups to be able to investigate different components (seal/rod combinations) and scales, which in turn required new sensors and sensor configurations. To investigate the ocean rod sealing systems it was necessary to include water exposure in the system, for which a water tank was designed.

Previous versions of the dynamic seal rig had issues with data management and would frequently lose data at higher sampling rates. The data labelling was also not sufficiently structured to be able to use with machine learning algorithms. For these reasons an overhaul of the software systems was planned.

Lastly, the sealing model that is included in CPO's Wave-To-Wire (W2W) model is a very simplified model of the sealing system – equating speeds to frictions through a simplified Stribeck model. Here we develop and implement an advanced seal component model capable of better representing the complexities of the dynamic sealing systems in a simulated environment.

3.2 Hardware upgrades

3.2.1 Test rods

Several test rods have been designed and procured to represent the dynamic sealing systems on the CorPower Ocean WEC. These systems are described in detail in D3.1 [1]. The rods all consist of a carbon steel base material with a metallic coating for wear and corrosion resistance.

Table 1 summarises the constitution of the alloys used to coat the rods representing the different components. These rods were produced for 1/4th scale (80 mm) and full scale (350 mm).

Table 1: An overview of the different coatings investigated.

Represented sealing system component	Surface coating	Coating nominal thickness
Pre-Tension Cylinder	Hard chrome plating	100 microns
WaveSpring Cylinder	Nitrocarburizing	N/A (diffusion process)
Ocean rod	Laser cladded Ni-superalloy	250 microns

3.2.2 Sealing setups

Different sealing sets were designed and procured to represent the following components in the seal rig:

- Pre-tension Cylinder
- WaveSprings

- Ocean rods

An overview of each of these systems is given in D3.1 [1] . Seals for the pre-tension cylinder and WaveSprings were designed to be tested at ¼-scale in diameter (80 mm). Ocean rod seals were designed to be tested at both ¼-scale and full-scale to be able to investigate scaling effects in the diameter of the sealing systems.

To simulate advanced wear states of the gliders, reduced diameter o-rings were used, together with shimming components in the sealing grooves (see Figure 2). This enabled precise adjustment of the seal clamping force, which can approximate different levels of wear on the seals.

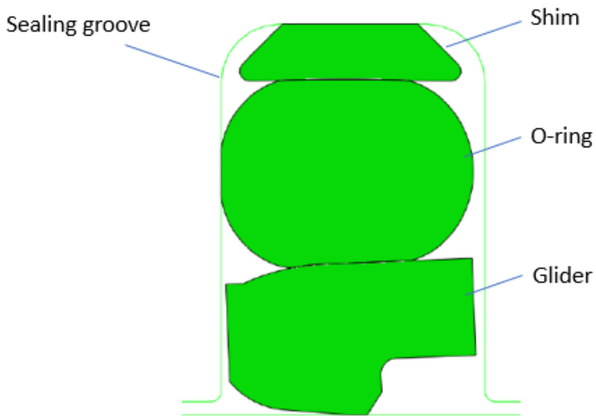

Figure 2: Illustration of cross-section of sealing groove, with components including: shim, o-ring, and glider.

3.2.2.1 Scraper seals for ocean deployments

Scraper-type seal designs were also iterated to find a design solution that worked best to remove accumulated biofouling from the rod surfaces. Testing in other projects has shown that biofouling can in extreme cases ingress into the sealing gland and contaminates the lubrication fluid, which can result in more wear.

The previous designs were analysed, and new concepts were developed for ocean testing. These concepts investigated different ways of creating more downforce at the leading edge of the seal to prevent fouling ingress, as well as ways of more effectively diverting accumulated fouling away from the seal gland opening. This involved:

- Modifying seal profile geometry
- Adding extra components such as metallic springs & o-rings
- Removing double-acting function from the seal profile

This involved designing a more modular interface to aid the swapping in/out of different scraper systems.

3.2.3 Sensor configuration

The sealing chamber design allows sensors to be easily reconfigured between different trials. There are 10 ports on each of the 4 ¼-scale chambers that allow sensors to be placed in

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positions of particular interest (see Figure 3). It is also possible to connect sensors on the lines in and out of the chamber (e.g., on the oil in/out, or the high-pressure air in/out).

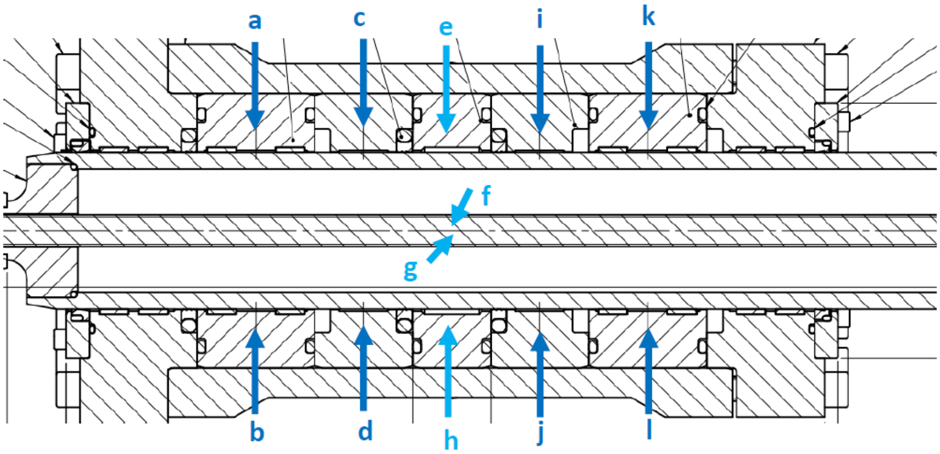

Figure 3: Sensor ports on a sealing chamber. Each of the arrows shows a location at which a sensor with a G1/4 fitting can be connected. These can be e.g., flow, temperature, or pressure sensors.

In this case, the sensor configuration for the dynamic seal test rig was designed to investigate the following parameters:

- The intra-seal pressure (between e.g., primary & secondary seals)
- The lubrication temperature prior to, and directly after entering the sealing chambers

These parameters were identified as having a lot of potential for giving indications of the sealing state of health. Figure 4 shows an example of the sensor setup for the initial machine learning trials that were conducted.

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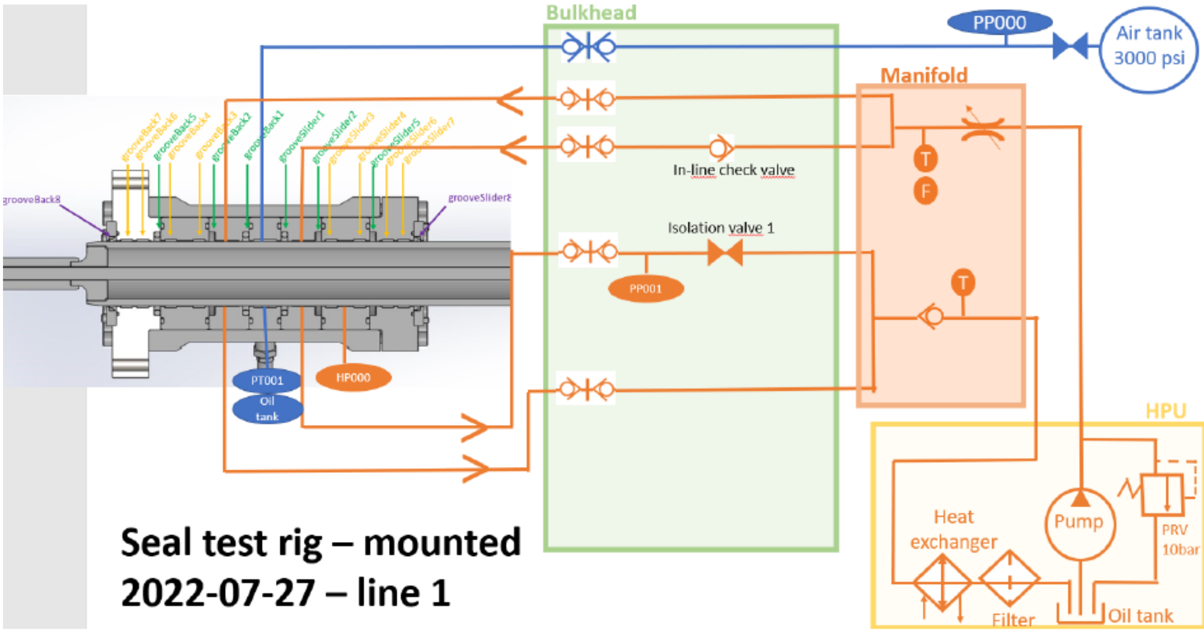

Figure 4: Schematic of the sensor setup used for the initial machine learning trials. Here, HP000 and PP001 represent pressure sensors monitoring the intraseal pressure.

3.2.4 Full-scale rod setup

In order to investigate the scaling effects in terms of diameter, a full-scale rod setup was designed. This involved a total overhaul of the rig rod/chamber setup. The setup then consists of a single full-scale rod, rather than 4 ¼-scale rods.

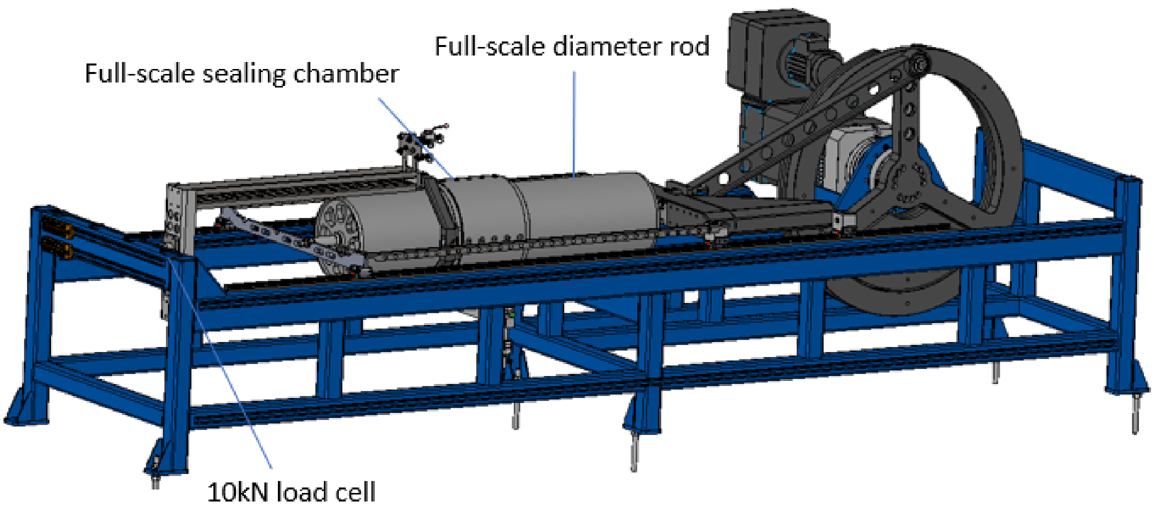

Figure 5: Illustration of design for full-scale diameter ocean rod in test rig.

3.2.4.1 Full-scale rod design

It was decided to investigate the ocean rod in a full-scale version. The full-scale rods have the same design as the ¼-scale rods, only larger diameter. It also has the same dimensions as full-scale ocean rods used in the C4 WEC. The thickness of the cladding was kept the same to be representative of the WEC system. Two rods were designed and ordered, with the key difference between the two being the cladding coating alloy. This was to allow comparison of the different alloys in terms of wear and corrosion.

Table 2: Description of full-scale ocean rod coatings.

Rod	Laser-clad alloy coating	Coating nominal thickness
Full-scale rod A	Ni-superalloy	250 microns
Full-scale rod B	Ni- superalloy, reinforced	250 microns

3.2.4.2 Full-scale rod chamber

The rod chamber was designed to be representative of the WEC system. The chamber can accommodate both PTC and ocean rod sealing systems. All grooves have the same dimensions, and the seals sequence can be the same as the real-life systems. The chambers can accommodate the same sensors and lubrication connections as the ¼ scale chamber, so that the signals are comparable.

3.2.4.3 Attachment to rig

The friction arms and yoke had to be redesigned to accommodate the larger diameter rods and expected higher frictional levels. The design of the attachments therefore includes some new parts but also re-uses some existing ones.

An important scaling effect is linked to the stiffness of these attachments. Indeed, higher forces will be transferred trough only one line instead of four parallel lines. To avoid excessive vibrations at the turning points, the new system had to be made proportionally stiffer.

3.2.4.4 Load cells

The 5 kN load cells for the ¼-scale rods could not be used for the full-scale rods as the friction forces were predicted to be considerably higher. It was briefly considered to use two 5 kN load cells in parallel to measure the total friction force, but it was decided that it would be more straightforward to opt for a single larger capacity load cell. A 10 kN load cell with the same form factor was therefore procured and integrated.

3.2.5 Water-chamber setup

Augmenting the dynamic sealing test rig with a water-chamber allows an evaluation of the media separation between lubrication and water. This separation is important to keep the biodegradable oil from mixing with sea water, which could cause its degradation and affect its lubricity, eventually requiring more maintenance operations.

Including a water-chamber on the seal rig is relatively complex, as the water needs to remain contained to protect the rest of the rig from corrosion, as well as protecting the electronic components. The containment should not adversely impact the motion of the rig, nor significantly alter the friction profile measured from the load cells.

A couple of different concepts were investigated. These included:

- A simple secondary sealing chamber at one end of the water chamber, with the other end interfacing with the sealing chamber to be investigated (see Figure 6a).
- Two full sealing chambers with a water chamber in between (see Figure 6b)

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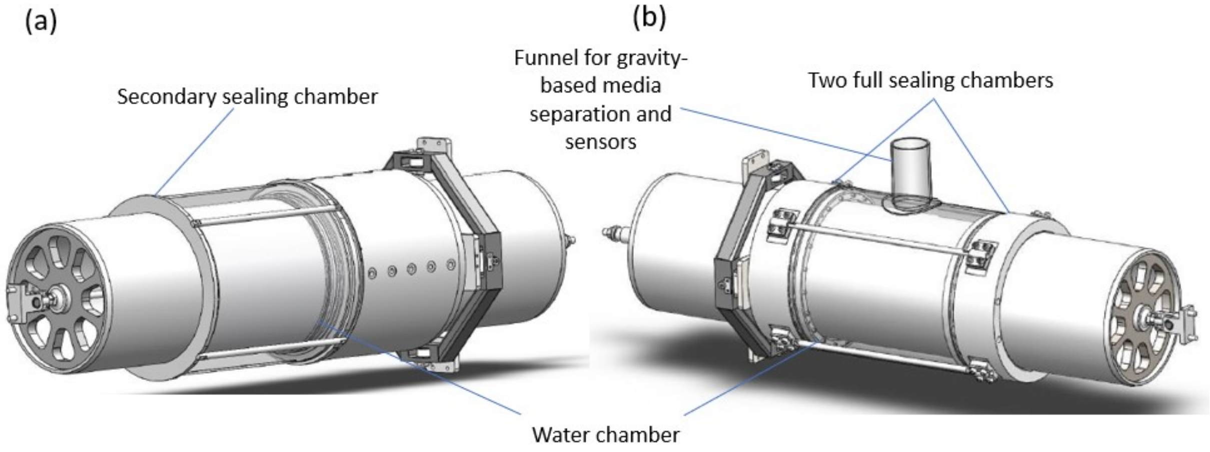

Figure 6: Illustrations of the conceptual designs for the water chambers. (a) Water chamber with simple secondary sealing. (b) Water chamber with two full sealing chambers.

After progressing with conceptual designs for both concepts it was decided to go ahead with a simple secondary sealing system (Figure 6a). The two-sealing chamber solution potentially opened for more parallel testing but requires high pushing forces with a risk that the machine cannot provide such forces. The decision was taken to speed up the design and implementation process.

The chamber itself is manufactured from a clear polymer to allow visual observation of the media behaviour. This was complemented by a saddled funnel at the top of the chamber (see Figure 6b). This allows liquid detector sensors to be implemented, as well as giving a visual reference of the oil-based lubrication leakage from the sealing chamber into the water.

One of the constraints on the system is the total length of the sealing chamber and water chamber. This places a limitation on the stroke length of the system. The design of the seal rig actuator allows for sinusoidal stroke lengths between 1000 mm and 400 mm. For the current design the maximum stroke length is the shortest available – 400 mm.

To be able to test multiple scrapers designs, the holders were designed modular. This can then be interchanged to easily test different scrapers.

The diameter of the tube needed to be as small as possible to keep the weight of the water down, while still leaving enough room for the modular scraper holders and the sealing systems. The final inside dimension is 420 mm with a wall thickness of 6 mm.

Due to the manufacturing process of the transparent tube (large tolerances), the sealing solution between the interface and the tube had to be able to take up a varying gap.

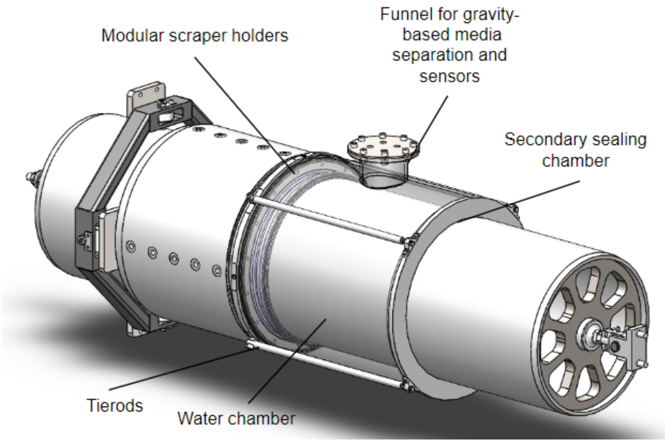

Figure 7: Water exposure chamber as per final design.

3.3 Software upgrades

3.3.1 Seal rig software

The VALID test plan includes trials of advanced monitoring of sealing systems. This is expected to improve WEC maintenance strategies (towards predictive maintenance), but also to accelerate the validation of different new designs in the seal test rig.

The seal rig's software therefore received an overhaul, to enable more reliable data capture, and accurate data labelling from each sensor signal and test setup to allow detailed post-processing using e.g., machine learning algorithms for feature detection.

This activity included the separation of the logging tasks between different computers, programs, and databases as illustrated on Figure 8. New interfaces for data queries and monitoring were also developed.

According to the test results and the orientation of the test plan, it is expected that further software improvements might become necessary.

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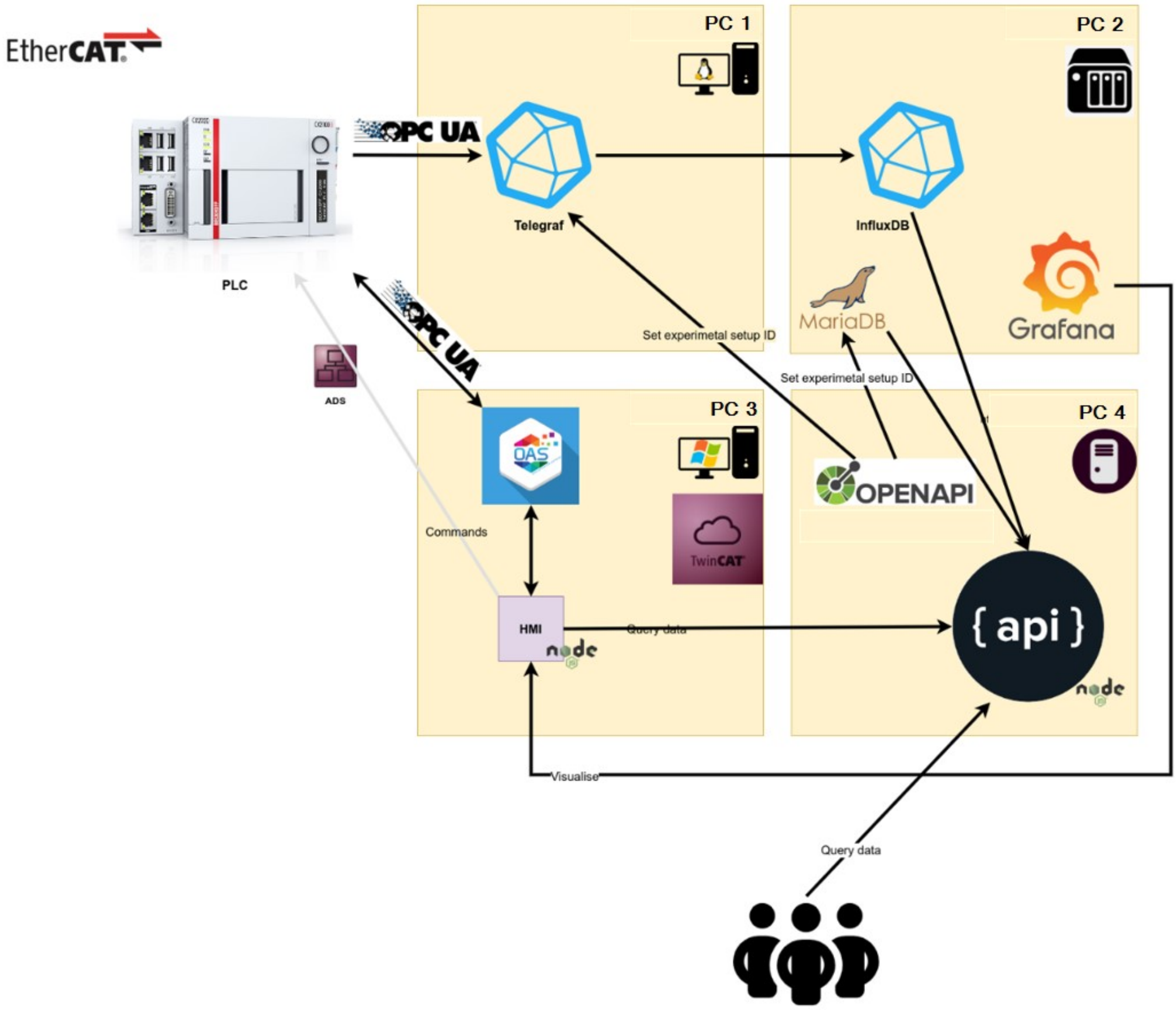

Figure 8: Schematic of overhauled software design for seal rig.

3.3.2 Advanced sealing component model

The initial outcomes of the task "software and modelling" presented in D3.1 [1] are covered herein.

3.3.2.1 Component models for hybrid testing

The User Cases of the VALID project intend to demonstrate different approaches of hybrid testing as a way to accelerate the development and validation of wave energy devices.

After discussions with AVL and other key project partners throughout the first half of the VALID project, it was identified that live hybrid testing, as defined in the automotive industry, is already extensively done at CPO in the PTO (Power Take Off) testing phases, often referred as "PTO dry testing".

The tests executed at component level in the seal test rig, however, are not suited for hybrid testing replicating real operational loadings, mostly due to the test rig's stroke limitations. The seal test rig has a maximum stroke of 1 m (adjustable mechanically, but not continuously controllable) while the full system has 7 m stroke. Furthermore, it is also not able to generate the wave-induced stroke of different amplitudes that a WEC would experience. In these conditions, it is impossible to model in real time the dynamics of a full WEC and to do live co-simulation in the seal rig, which is at the core of hybrid testing.

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The seal test rig is instead designed to operate continuous sinusoidal motion of fixed stroke, for testing on long travelled distance. The analysis output is a calibration of friction forces over a full range of sliding speeds (-4 to +4 m/s) and potentially of accelerations, and of wear over these distances.

This type of isolated component calibration is very common in the automotive industry and used in hybrid testing as building blocks that are part of the global hybrid models.

This work package therefore aims as contributing to the VALID methodology by the elaboration of advanced **component models** that can then be used with the following objectives:

- **create and calibrate an advanced virtual "component block" that can be used in full-PTO hybrid testing.**
- validate components designs (in small test rigs instead of in full-PTO test rigs)
- validate scaling effects (to be able to do simpler and cheaper tests)
- simplify/ homogenize data post processing between the different test setups
- design and validate advanced monitoring systems

There is therefore no plan to upgrade the seal test ring with different strokes, but rather to parametrize the component models in a way that can easily incorporate the test stroke.

3.3.2.2 Seals component models

The current seal component model used by CPO for calibration and for full-PTO hybrid testing mostly focusses on friction, through Stribeck models. These models contain friction parameters (coulomb, viscous, stribeck coefficients) and are fitted for experimental data through manual post processing scripts.

This has been shown to be efficient at predicting performance levels (friction forces and loss power) but does not allow for fine leakage and wear monitoring, during the tests or in the WEC application.

It is believed that developing an advanced component model that connects to more physical behaviours (more parameters, functions and in- and outputs) can solve the above limitations.

This advanced model is considered as an outcome of the work package and will therefore be described in the upcoming deliverables. However, the elaboration of the model already started with discussions with different suppliers, and a literature review was carried out by Y4C.

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4 Implementation of Upgrades

4.1 Description of implementation

4.1.1 1/4th scale Test rods and sealing components

Some of the 1/4th scale tests were carried out with existing rods and seals that CorPower had in stock from previous projects. If the scaling method is validated, tests might return to small scale to allow for parallel testing. In that case, more small-scale rods and seals will be ordered to the different manufacturers.

4.1.2 Sensor configuration

The sensor configuration was easy to modify between tests due to the well-planned design of the sealing chambers. Each of the sensor configurations will be described where appropriate for each of the tests in the upcoming deliverables of the VALID project.

4.1.3 Full-scale rod setup

The two test rods were ordered and received at the CPO offices in Stockholm, Sweden, see Figure 9. These rods were then integrated in the seal test rig with the full-scale chamber, new attachments, and new load cell (Figure 10).

Figure 9: Full scale rods at delivery to CPO Stockholm office.

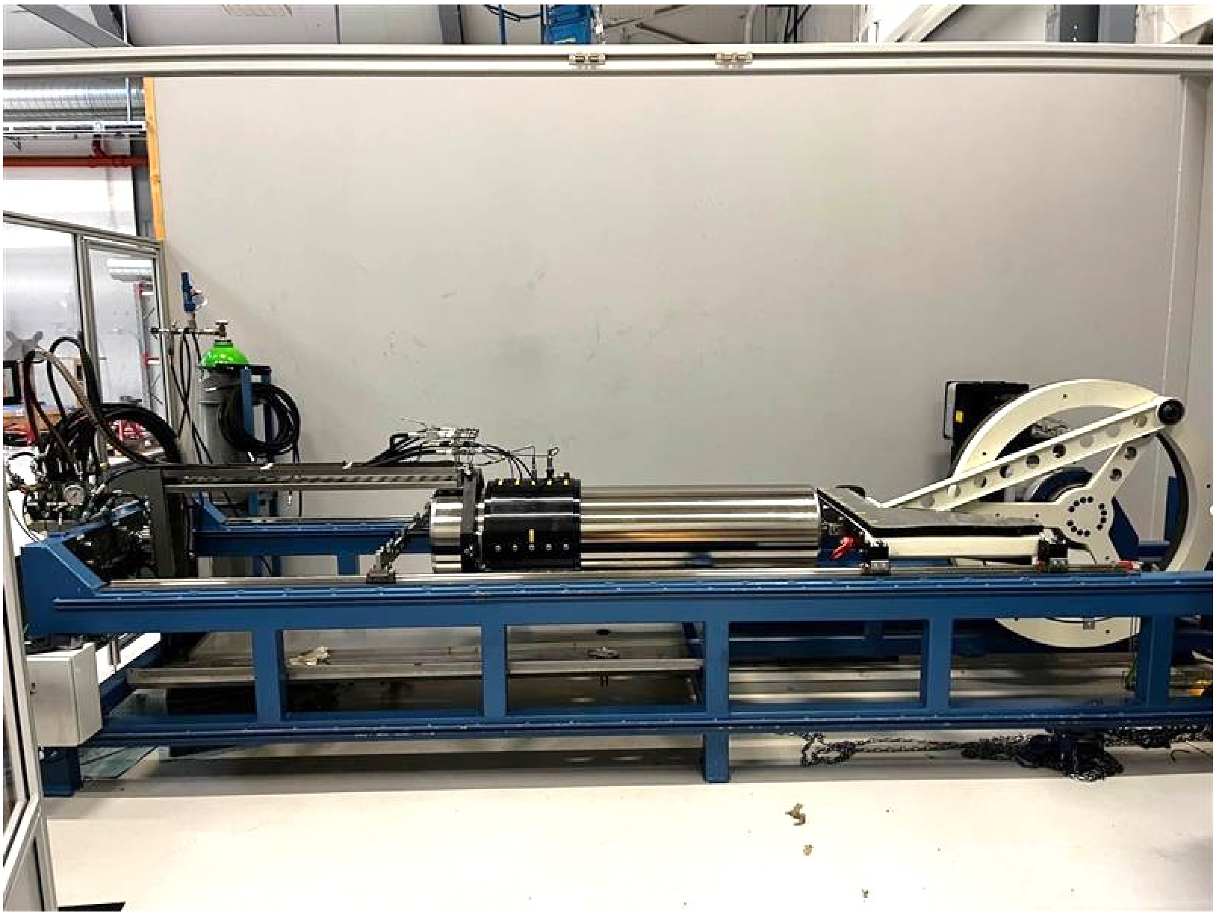

Figure 10: Full-scale seal rig assembly completed.

4.1.4 Water-chamber setup

The full-scale water chamber was designed, see Figure 7, but not yet received or assembled. It will be procured, assembled, and tested through the test program in 2023 as per D3.1 [1]. Results will be presented in the following VALID deliverables.

5 Conclusions

This report shows the upgrades that were made to the seal test rig as part of CorPower's User case (UC1) of the VALID project, both in term of hardware and software.

The first part of the test program (Machine Learning demonstration with advanced monitoring techniques) required minimal new hardware but some smart adjustments of valves and sensors, as well as a major rehaul of the seal rig software with better data labelling and storing.

The second part of the test program, during January-February 2023 required design, sourcing, and assembly of the first full-diameter rod and chamber in the seal rig. This setup is now physically assembled and under testing.

An important aim of the seal test rig is to support building advanced sealing component models to be used in the wave-to-wire model and "PTO dry testing", which represents a true hybrid testing set-up.

A design extension was created for water exposure in the seal test rig. This design will allow the monitoring of media exchange (oil/water) and guide the design of the ocean-facing seals and scrapers.

More upgrades might be needed along the test program (see D3.1), according to the previous results. These upgrades will be documented in the subsequent deliverables or as updates of D3.2.

6 Nomenclature

Abbreviations

EC	European Commission
EU	European Union
H2020	Horizon 2020
PTO	Power Take Off
UC	User Case
W2W	Wave-To-Wire model
WEC	Wave Energy Converter
WP	Work Package

7 References

[1] R. Harnden, A. Bonel, J. Lindén, P. Johannesson, and J. Sandström, 'VALID Deliverable 3.1: User case and methodology report for User Case 1', 2022.
[2] Waveboost D3.6, 'WaveBoost Deliverable D3.6 Reliability Testing', H2020 Project Deliverable Deliverable D3.6, Oct. 2019. [Online]. Available: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5c8e7279f&appId=PPGMS