Final report

1. Project details

Project title	Digital hydraulic PTO for Floating Power Plant (DigitalPTO)
File no.	64019-0047
Name of the funding scheme	EUDP
Project managing company / institution	Floating Power Plant A/S
CVR number (central business register)	28143893
Project partners	Aalborg University Sea Systems AS (Scana offshore)
Submission date	23 December 2020

2. Summary

2.1 English version

The Danish hydraulics sector is world leading, particularly within the wind industry. The technical concept known as “digital hydraulics” has a great potential in renewable energy applications, as it offers a cost-effective and very controllable way of handling the large forces associated with renewable energy.

The DigitalPTO project advanced the state of the art for digital hydraulics by applying the concept as a Power Take Off system (PTO) for the wave part of the hybrid wind and wave energy platform, which is developed by the company Floating Power Plant (FPP). In the project, an existing dry test-rig with a small-scale digital hydraulic PTO was combined with novel, advanced control strategies.

In the beginning of the project the PTO test-rig were upgraded to enable implementation and validation of advanced control strategies. The upgraded test-rig were used throughout the project for developing and validating models and control strategies. The project resulted in FPP having an updated conceptual design of a wave energy PTO system that is both fully compatible with the latest updates in platform design and have a matching robust and validated control strategy.

The project is feeding directly into the next steps of the PTO development, which are to build and optimize the PTO at full scale, first in a dry test-rig and afterwards in a real-sea demonstrator.

2.2 Danish version

Den Danske hydraulik sektor er verdensførende, ikke mindst inden for vind industrien. Det tekniske koncept kendt som “digital hydraulik” har et stort potentiale inden for vedvarende energi, på grund af dets evne til at håndtere de store kræfter, som findes i vedvarende energi på en kontrollerbar og kosteffektiv måde.

DigitalPTO projektet fremmer ”state of the art” for digital hydraulik ved at anvende det som energiudtag (PTO) fra bølgekraften til elektricitet på den kombinerede bølge- og vindenergiplatform, som udvikles af firmaet Floating Power Plant (FPP). I projektet blev en eksisterende tør-testrig med et digitalhydraulisk PTO i lille skala kombineret med nye avancerede kontrolstrategier.

I starten af projektet blev PTO testriggen opgraderet til at muliggøre implementering og validering af avancerede kontrolstrategier. Den opgraderede testrig blev anvendt gennem projektet til at udvikle og validere modeller og kontrolstrategier. Projektet resulterede i, at FPP fik et opdateret konceptuelt design af et bølgeenergi-PTO-system, der er fuldt kompatibelt med de nyeste opdateringer inden for platformdesign og har en matchende robust og valideret kontrolstrategi.

Projektet leder direkte ind i de næste trin i PTO-udviklingen, hvilket er at bygge og optimere PTOet i fuld skala, først i en tør testrig og derefter i en fuld demonstrator til havs.

3. Project objectives

The project further developed a digital hydraulic Power Take Off (PTO) for wave energy systems, coupled with advanced control strategies, with particular focus on implementation for the project partner Floating Power Plant A/S (FPP).

FPP are in the final development phases of its patented wind and wave energy hybrid platform “P80”. As show in Figure 1 the P80 is essentially a floating foundation for a large offshore wind turbine (up to 8MW), with integrated wave energy converters. The wave energy converter consists of a wave absorber that performs a pitching motion when excited by waves; and a power take off system (PTO) that converts the energy in the pitching motion into electrical energy. A P80 platform has four wave absorbers each with its own dedicated PTO system. One common grid-side power converter is however shared by the four PTOs.

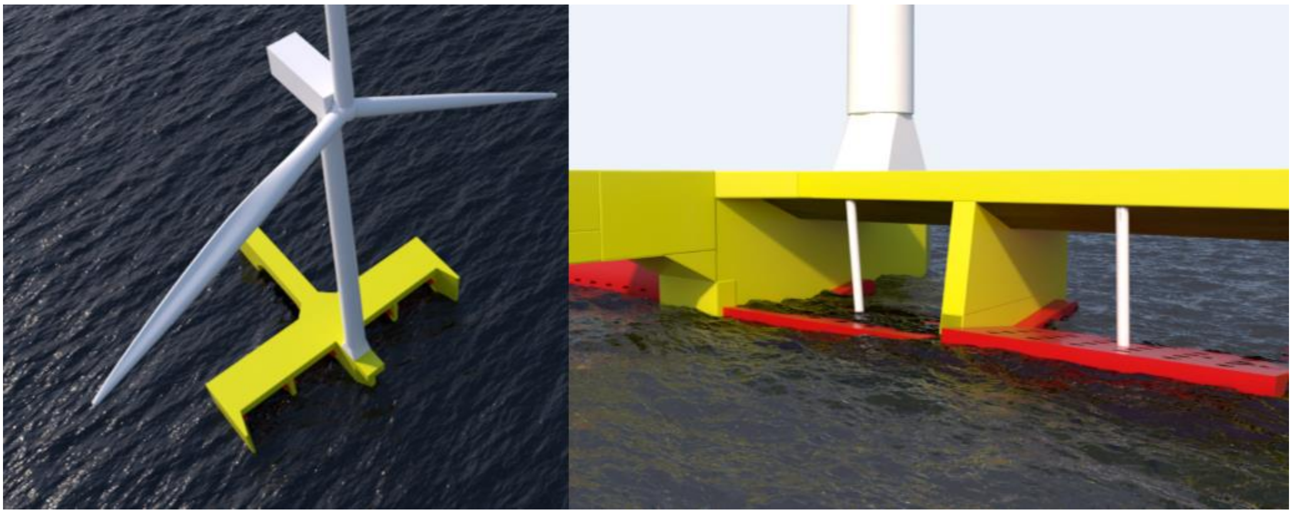

Figure 1. Composite picture - the P80 platform and zoom on Wave energy converters.

Shortly explained, a wave PTO is the component that convert the mechanical energy, captured by the wave absorber, into useable electrical energy. The captured mechanical energy comes in the form of motion, characterised by low speed and high forces. One of the most important features of a wave PTO is that is must be able to handle these high forces, while operating at a high efficiency, without being very expensive.

One of the most promising technologies for achieving these features is the “digital hydraulic PTO system”. In this type of PTO the (counter)force applied to the wave absorber can be controlled, by turning a number of piston pump areas on or off. This means that the wave absorber can be optimally dampened, and the PTO can operate close to its peak efficiency. The system can be implemented using standard industrial hydraulic components, and standard generators and converters, which ensure cost competitiveness compared to systems requiring tailored components. The mechanical components in FPP’s PTO are shown in Figure 2.

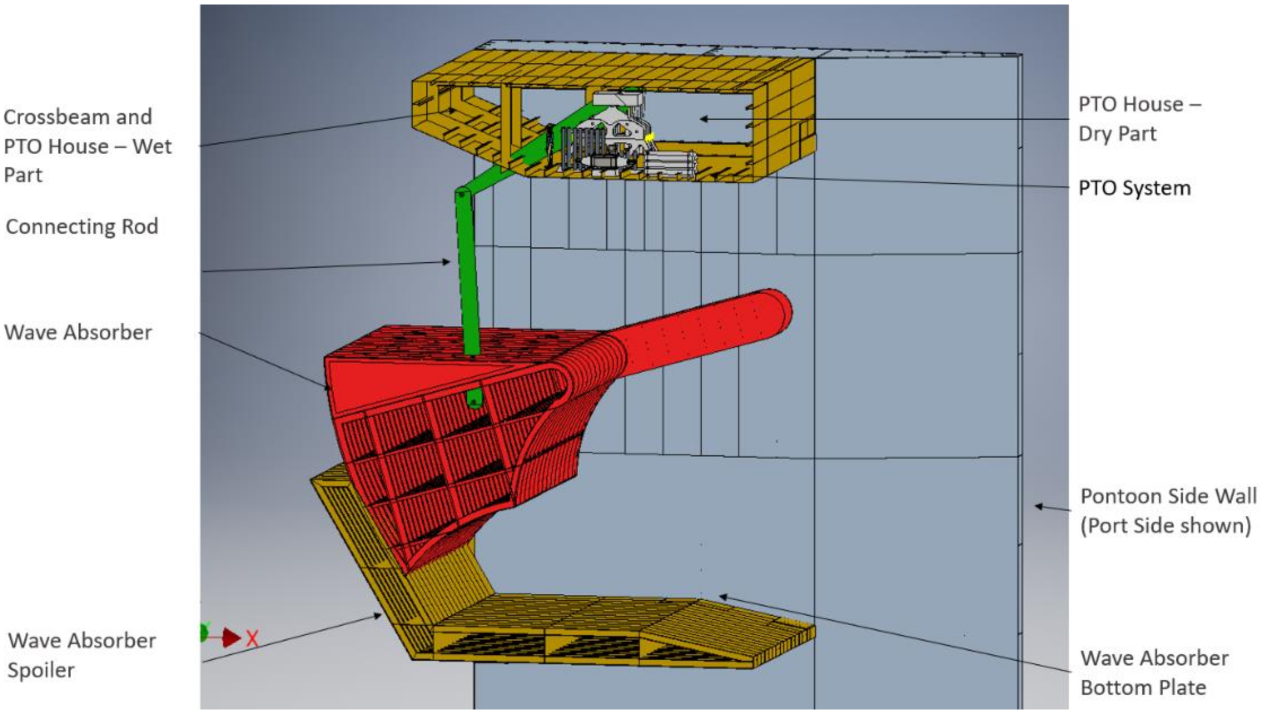

Figure 2. Cross section of the P80 platform - showing the wave absorber and the digital hydraulic PTO.

The digital hydraulic PTO moves a lot of its functionality from the physical domain to the control system domain. In order to take full advantage of the flexibility the digital hydraulic system offers, a solid understanding of the interplay between the physical- and control system domains is needed. This project gained that knowledge by simultaneously developing a numerical model of the PTO and control system and conducting empirical tests on a scaled version of a digital hydraulic PTO system.

Tests on the scaled version of the PTO system was carried out on a so-called dry-test rig. The test-rig consists of two systems, the scaled version of the PTO (system under test) and a wave simulator. In the wave simulator the wave absorber (the part that is moved by the waves) is replaced with a hydraulic piston. This piston is then controlled by a numerical simulation of the absorber motions when hit by waves. The purpose of a PTO dry-test rig was to be able to perform experiments with different configurations of the PTO hardware and different control strategies (code), on dry land. This setup has huge benefits compared to experimenting on a real platform in the sea, as the system is always available independent of weather conditions, and as the same wave conditions can be tested with different setups (repeatability) – hereby allowing optimisations to take place in a structured manner, at lower costs.

After successful calibration and validation of the numerical model, a range of control strategies were explored both using the numerical model and the scaled PTO test-rig.

The end products of the project were:

- A numerical model that can be used to reliably simulate FPP's digital hydraulic PTO system, under different control strategies;
- A set of promising control strategies for the PTO system, in the sense of efficiency, reliability, durability and cost of energy;
- An updated techno economical model (cost model) for projects using FPP's technology, taking into account the advancements in the PTO system.

4. Project implementation

The dry-test rig shown in Figure 3 was upgraded and used for the testing in the current project.

Figure 3. Floating Power Plants small-scale PTO dry-test rig at Aalborg University.

The project started on 1/9-2019 and followed the original schedule until February 2020, see original schedule in Figure 4. In parallel with this project, other technology development was underway (including the EUDP project j.nr 64019-0833 regarding decarbonisation of Oil Gas production) as well as commercial development with a demonstration project in Spain and several projects in the UK and Ireland. The progress and requirements of these projects, in particular the O&G EUDP project, only made this EUDP PTO project more relevant. To increase the competence base in "WP5 Design adaptation" and thus ensure a better link to the other projects, the partners proposed to add a new industrial partner Scana Offshore and transfer some funds in the budget. In this way, the project was able to be implemented within the original grant amount, and with fulfillment of the original goals, as well as in addition mean that the project results will be more useful in other of FPP's projects, and the research would also be significantly better at project completion. The changes are described in detail in a separate document and was approved by EUDP.

The outbreak of Covid-19 during the project has significantly reduced the foreseen travel activity for internal meetings and conference participation. This situation has largely been delt with by rearranging meetings at virtual meetings. As described in the yearly report from 30 June 2020 the Covid-19 situation lead to the closure of AAU's laboratory facilities. Therefore it was not been possible to the same extent as expected to continuously validate the model development up against tests on the test-rig. Among other things, this meant that milestone M3 "Numerical model of test rig is implemented and documented" was not yet reached (on 30 June 2020). However, the work was well underway, and progressed according to plan with a delay of 3 months. The project was extended as shown in Figure 5 (approved by EUDP) till end December 2020, and thereby the successful finalisation of the project was realised.

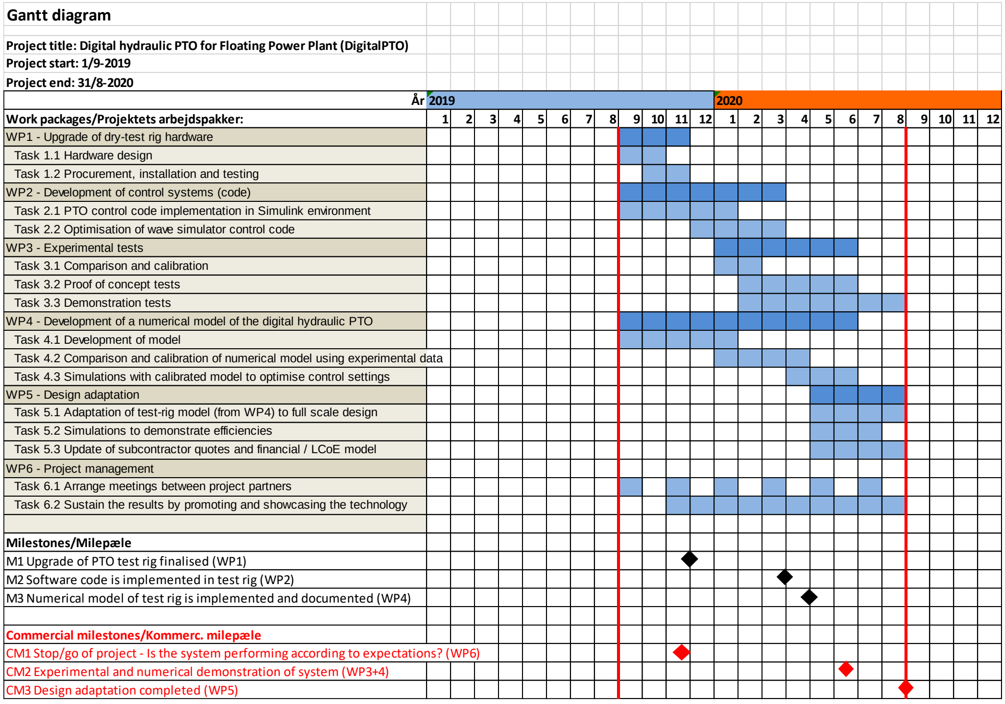

Figure 4. Gantt chart from application by 1 March 2019.

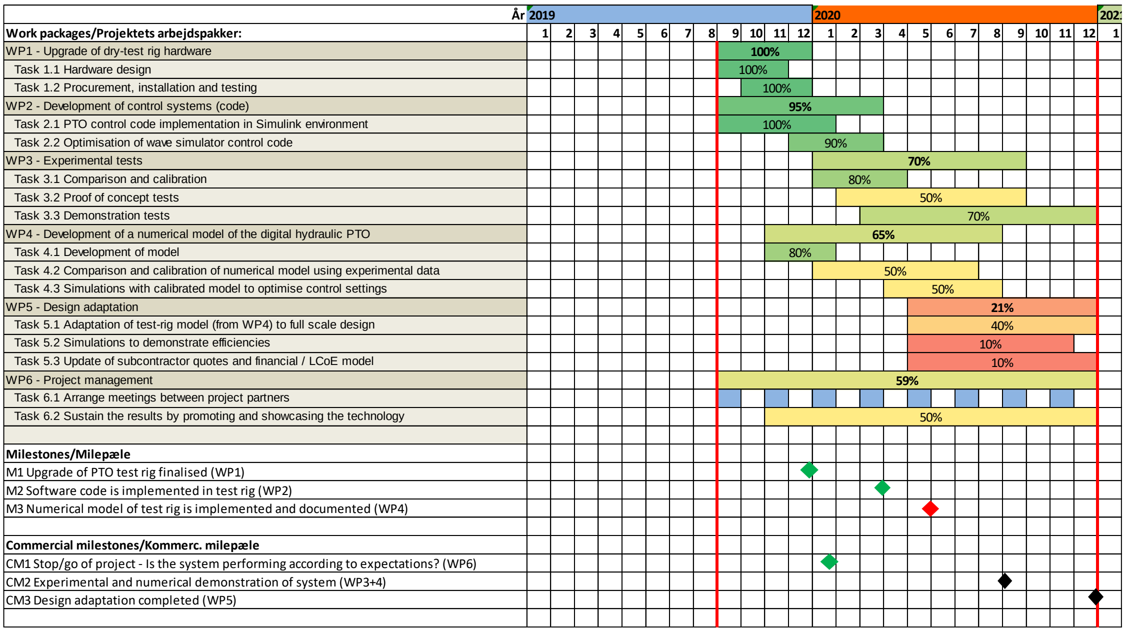

Figure 5. Updated Gantt chart by 30 June 2020.

5. Project results

To obtain the highest possible efficiency of the PTO system a digital hydraulic solution has been developed by FPP, which enables the components to operate at or very near their optimum, hereby avoiding part load efficiency drop. The PTO damping torque is applied to the yoke with hydraulic cylinders; A simple sketch of the PTO system is seen in figure 5 featuring two cylinders as in the current test-rig system. The full scale P80 PTO will include more cylinders.

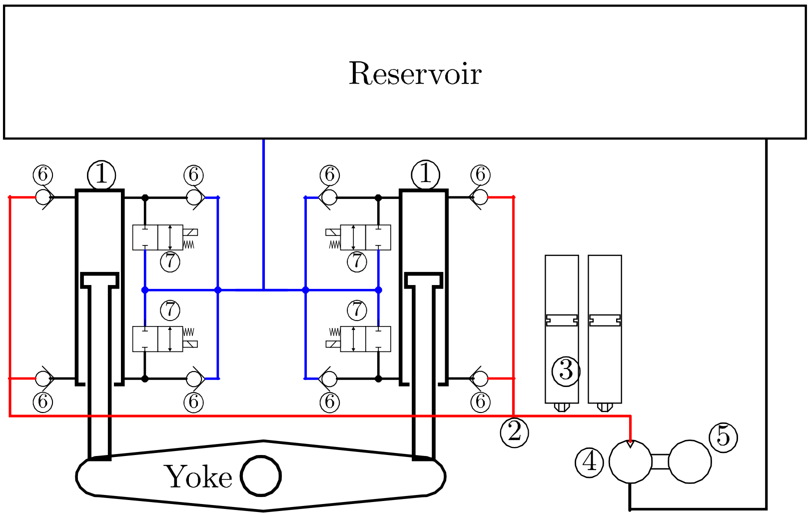

Figure 5 Simple illustration of the Digital hydraulic PTO system with two cylinders as in the small scale PTO system.

Development and tests completed in the current project on the scaled version of the PTO system was carried out on the so-called dry-test rig. The test-rig consists of two systems, the scaled version of the PTO (system under test) and a wave simulator. In the wave simulator, the wave absorber (the part that is moved by the waves) is replaced with a hydraulic piston. A numerical simulation of the absorber motions generates position and velocity references to the wave cylinder such that the PTO system experience movements as if deployed at sea. Figure 6 illustrates the control structure for the wave cylinder in the dry test-rig.

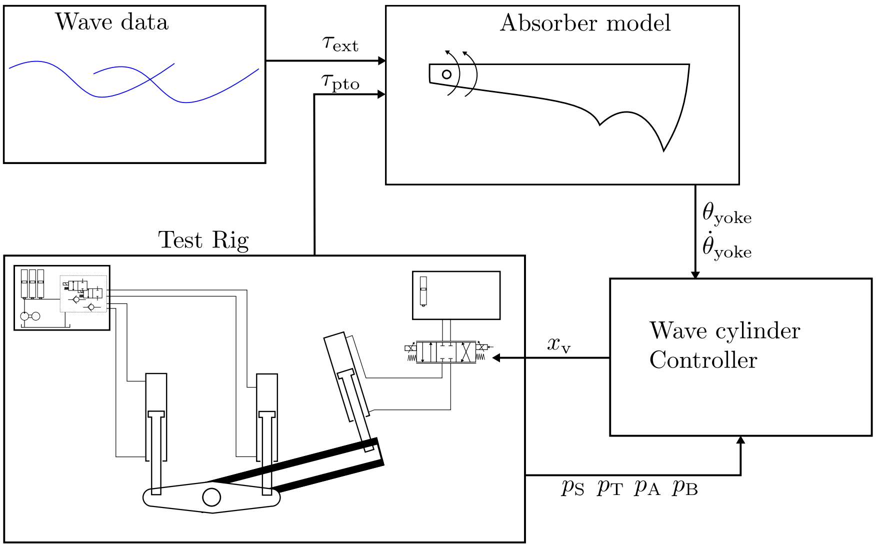

Figure 6 Illustration of control structure for the Test-Rig wave cylinder.

The purpose of a PTO dry-test rig was to be able to perform experiments with different configurations of the PTO hardware and different control strategies (code), on dry land. This setup has huge benefits compared to experimenting on a real platform in the sea, as the system is always available independent of weather conditions, and as the same wave conditions can be tested with different setups (repeatability) – hereby allowing optimisations to take place in a structured manner, at lower costs.

After successful calibration and validation of the numerical model, a range of control strategies were explored using both the numerical model and the scaled PTO test-rig. A few of the main results from the test-rig is given below.

Four PTO control strategies were studied in the project. These are Linear Damping, Coulomb Damping, FPP Simple and FPP Digital. The damping torque of the linear damping control algorithm is simply the yoke velocity multiplied a damping constant while the damping torque of the coulomb control algorithm is a constant coulomb torque multiplied by minus the sign of the yoke velocity.

The FPP Digital control algorithm is an event based model predictive algorithm using an internal model prediction to run an optimisation routine calculating the PTO torque choice yielding highest average absorbed power. The internal PTO torque optimisation is run in the event of yoke motion changing direction; i.e., corresponding to the velocity being zero.

For the three above mentioned algorithms the generator torque is controlled such that the system pressure is held relative constant.

The FPP Simple control algorithm gives a generator torque reference based on a polynomial with the generator velocity as input, while the on/off valve settings are controlled by the system pressure, such that low system pressure yield low pumping area, medium pressure gives medium pumping area and high pressure asks for high pumping area. The FPP Simple is the baseline algorithm utilised at earlier offshore tests of the so-called P37 platform.

The linear damping has only been implemented in the numerical model, as the current test-rig may only apply discrete torques. Further “FPP Simple” is only run in the test-rig as the numerical model does not include a full hydraulic model, which is requested for the FPP Simple algorithm.

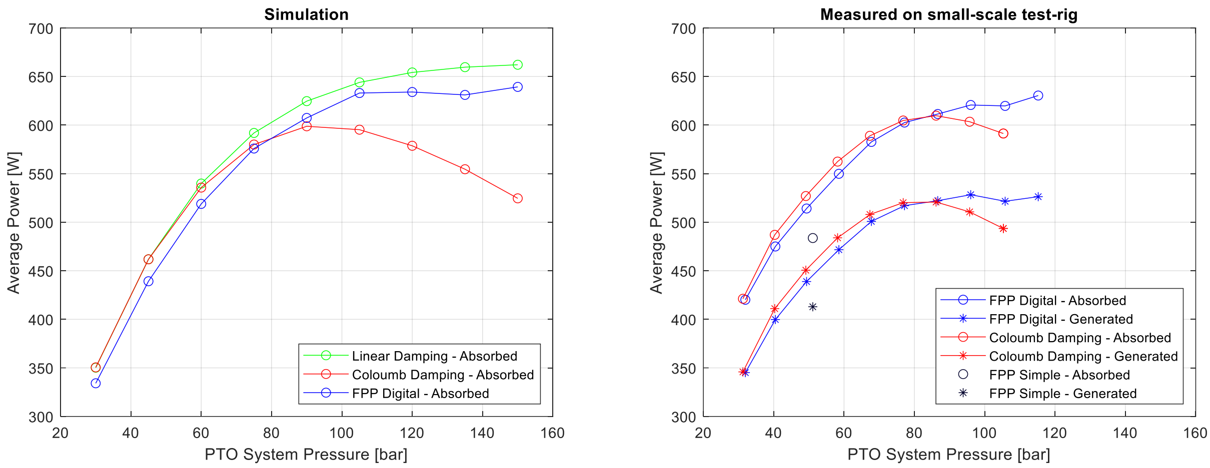

Figure 7 Results from the small-scale test-rig at AAU. Power performance in irregular waves. Left: Simulations, right: Measurements on test rig

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The plots in Figure 7 shows the average power absorption at various system pressures. The power absorption of the coulomb damping algorithm is seen highly dependent on the system pressure level whereas both the linear damping and the FPP Digital are seen to deliver high power absorption as long as the pressure is sufficiently high. The FPP Simple yield only one system pressure setting as this is not variable in this control structure.

For comparison the maximal average absorbed power for the four algorithms is compiled in the table below. “FPP Simple” is used as the baseline when calculating improvements in power absorption on the test-rig PTO.

Control	Simulation	Measured on small-scale test-rig			
	Absorbed power [W]	Absorbed power [W]	Generated power [W]	Improvement [%]	Wave2Wire efficiency [%]
FPP Simple	-	483.7	412.9	0%	54%
Coloumb Damping	598.8	609.7	520.8	26%	68%
Linear Damping	662.1	-	-	-	-
FPP Digital	639.3	630.4	528.3	28%	69%

Figure 8 Results from current EUDP project - improvement of energy absorption and total (wave to wire) efficiency.

These test results show the large potential for improving the energy absorption and decreasing internal system losses when using the advanced control strategy. In Figure 8 it is seen that the total wave to wire efficiency has been improved from 54% to 69%.

Experience from the P37 offshore tests and the developments in the current project have strengthened the trust in the Digital hydraulic PTO system design for the FPP wave energy converter. The technology has proven robustness at offshore tests and numerical models and Scaled Test-Rig results have shown an increase in power productions with the novel developed FPP Digital Control.

A natural next step in commercialisation of the Digital hydraulic PTO system for the FPP P80 platform is therefore to design, construct and validate a full-scale PTO system.

5.1 Final demonstration in a wave basin

To prove the feasibility of the FPP concept towards the industry and potential customers a sophisticated model of the P80 platform were constructed and tested in the wave basin at Aalborg University in Denmark in Autumn 2020. Testing was done as part of the EUDP project “De-carbonization of Oil & Gas Production by cost effective Floating renewable Technologies” (J.nr. 64019-0833), but the testing included demonstration and validation tests of the control models, which were dedicated to the current project.

A total of 706 tests, of a scale 1:30 Floating Power Plant P80 platform, were completed during the 4-week campaign in the wave basin at Aalborg University (between 19 October and 13 November 2020). The platform was floating and moored to the seabed, and it included 4 individually real-time controlled wave energy absorbers with power take off systems to extract the wave power. A motor with a propeller was placed on top of the wind turbine tower to mimic the wind thrust force on the wind turbine rotor. The tests were completed on a variety of different setups, ranging from simple tests to characterize the P80 platform (e.g. flotation tests, mass distribution measures, hydrostatic tests, mooring response tests, waves basin without model, steady current on platform, WTG control with fixed tower, decay tests in calm water, WEC control with fixed platform in waves,...) to advanced tests with the floating platform in operation subject to misaligned 3D waves and unsteady turbulent wind. In the advanced tests the wind turbine thrust simulator was running in combination with real-time digital control of the power extraction from the wave energy converters. Among many force and motion measurements, the system included real time thrust generation and real-time rigid body optical motion tracking of the platform and absorber motions.

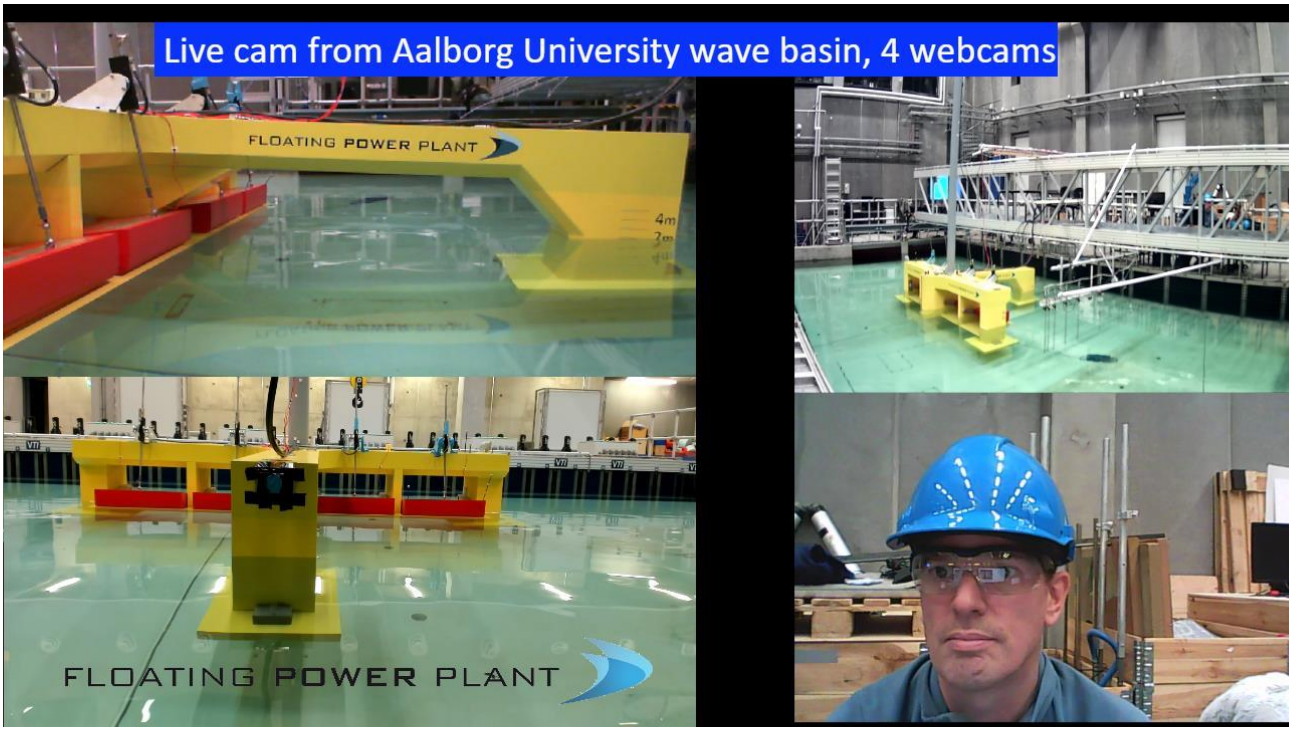

Figure 9. Screen shot of an online demonstration of the P80 testing at one of the webcasts.

Apart from the basin testing providing a massive amount of data for numerical model validation, an extensive demonstration program was executed. Originally it was planned to host physical visits to the basin testing for partners, clients, potential customers and other stakeholders. Due to the outbreak of Covid-19 it became evident that the physical presence would be significantly hindered. It was therefore decided to set up a remote visit concept, where a combination of presentation and web cast of live demonstration could create the sensation of physical presence, see Figure 9. This concept worked very well and FPP have had very good feedback from the more than 200 people that visited the tests either virtually or physically. More than 20 groups of external visitors were given tours to see the experiments in live action at the facility. During the events the model was demonstrated in operation in waves in the basin, including simultaneous control of the wind turbine simulator. For the virtual events 4 web cameras allowed streaming of online video of the experiments from various angles.

Throughout the testing period photos and videos were taken both for commercial/PR purposes and technical documentation. The material includes 565 photos and 135 videos.

Main conclusions from the campaign are:

1) The physical model (platform, moorings, wave energy absorbers, wind turbine) is built with exact precision of the shape (1 mm accuracy) and mass properties of all components is known with high accuracy. The model is working mechanically perfectly with practically no friction in bearings.
2) All sensors and measurements are of extraordinary precision and quality with almost no noise.
3) The wind turbine thruster can generate the dynamic thrust corresponding to the full scale 10 MW wind turbine in extreme design load cases.
4) The individual real time control of the wave energy absorbers is working with high precision with extremely low response times. Initial analysis shows that the wave power absorption performance is inline with the expectations and numerical simulation models.
5) The huge database of measurements from the test campaign are valuable inputs for numerical model validation and calibration.
6) The utilized setup (physical model, data acquisition and control systems etc.) are suitable for further and more advanced testing of the device in larger facilities (larger wave basins with higher water depths) in later test campaigns. Future tests will include e.g. extreme wave conditions and further investigations of influences of misalignment of waves, winds, and currents. The model is prepared for inclusion of more advanced mooring systems and complex multi degree of freedom wind force generators. The developed control system is set up to easily include communication via real-time inputs/outputs, e.g. for wind turbine control simulation software running on external systems as Software In the Loop (so-called "SIL systems").

6. Utilisation of project results

The project results have not generated increased turnover or exports yet.

The results of the project will be commercialised by FPP as part of the commercial deployment of their complete technology. The solution is marketed as part of FPP’s unique hybrid floating wind and wave system, delivering power in utility scale energy parks. FPP already have a developing pipeline of projects for this technology. These projects are significant infrastructure investments and typically have a development timeline of 3-7 years depending on scale. This project has ensured that the complete FPP solution is market ready in time for the pipeline of opportunities. The scale and operational importance of these projects dictate that the technology used is proven and reliable, being considered ”bankable”. While offshore wind is now considered well proven, and even floating offshore wind is maturing rapidly, wave energy is less mature and requires evidence of successful performance and operation. This development, testing and optimisation of the key wave energy system component will provide the validation of this part of FPP’s offering, making it suitable for commercial use.

Renewable energy is a key focus area for AAU. For more than 20 years AAU has been leading the Danish scientific activities in wave energy and has been active in most Danish and several international wave energy developments. Special knowledge is on the experimental and modelling side of both the entire WEC and the PTO-system. AAU's expertise is on techniques for measuring and analysis of acquired data, which includes performance investigation by wave2wire modelling and on studies using measurements from small-scale experiments and/or full-scale real-sea data. Also control strategies for wave power extraction in hydraulic systems is a key competence of AAU, which has been strengthened by the project.

Seasystems AS is a fully owned subsidiary of Scana ASA, a Norwegian company registered on the Oslo Stock Exchange under the ticker SCANA. The company supplies mooring solutions for the floating wind, aquaculture and oil & gas industry. The scope ranges from single components according to given specifications to full system delivery including analysis, 3rd party approvals, hardware supply and installation services. Seasystems has a history of supplying mooring equipment from the early 1990's in the oil & gas history, large aquaculture systems from in 2018 and the first major floating wind contract with Equinor's Hywind Tampen project in 2020. Seasystems main task in this project was the mechanical system for transferring wave forces from the wave absorber to the hydraulic PTO system. Seasystems is using the project learnings and results in the further development of the mechanical PTO design for the FPP device.

7. Project conclusion and perspective

This project has advanced the state of the art for wave PTO systems, by taking the PTO principle "The digital hydraulic PTO" from concept to a realistic small-scale rig, and has paved the way for a future project that will bring it to commercial scale. The concept is by far the most promising in the megawatt scale. However, the concept is still to be demonstrated and proven in commercial scale.

A new project will take that step towards a full-scale demonstration by taking previous lab and small-scale results and design a PTO system for a specific offshore demonstration project. More specifically the new project will design and construct a full-scale Digital hydraulic PTO system for the full-scale demonstration platform scheduled to be deployed at the Plocan test site in Spain by FPP. The design will be based on recent results from the small-scale dry tests and numerical simulations of the full-scale system. This involves designing the mechanical and hydraulic aspects of a full-scale PTO system for integration into FPPs hybrid platform.

8. Appendices

Homepage: http://www.floatingpowerplant.com/publicly-funded-projects/