Final report

1.1 Project details

Project title	WaveSpring for at forøge bølgeenergi absorption
Project identification (program abbrev. and file)	WaveSpring 64014-0156
Name of the programme which has funded the project	EUDP 2014-I, Særpulje
Project managing company/institution (name and address)	Aalborg Universitet Thomas Manns Vej 23 9220 Aalborg Ø
Project partners	Norwegian University of Science and Technology Wavestar A/S
CVR (central business register)	29102384
Date for submission	18-05-2018

1.2 Short description of project objective and results

English and Danish (600-800 characters)

The objective of this proof of concept project was to investigate the WaveSpring technology and how it can benefit wave energy converters. The WaveSpring concept is a negative stiffness component and this project had as goal to test the component on different wave energy converters. The negative stiffness component has as effect to reduce the hydrostatic stiffness of the converter, leading to a broadening of the frequency response of the converter that better matches the ocean wave spectrum .It was tested on a point absorber type and a pitching type of wave energy converter. The main result of the project is that the WaveSpring has indeed shown that it helps increase the power yield of the devices.

Formålet med dette blåstemplingsprojekt var at undersøge WaveSpring-teknologien, og hvordan denne kan bidrage til bølgeenergianlæg. WaveSpring-konceptet er en negativ stivheds-komponent, og målet for dette projekt var at teste komponenten på forskellige bølgeenergianlæg. Den negative stivheds-komponent har en reducerende effekt på den hydrostatiske stivhed på anlægget, hvilket medfører en udvidelse af frekvensgangen for anlægget, der passer bedre til havbølgespektrummet. Dette blev testet på bølgeenergianlæg af typerne point absorber og pitching. Slutresultatet i dette projekt er, at WaveSpring sandeligt har vist, at det hjælper til at øge energiudbyttet i anlæggene.

1.3 Executive summary

Harvesting wave energy has the potential of contributing substantially to the world energy mix in the future. It is a resource with relatively high power density and readily available along the coasts. The worldwide wave energy resource has been estimated to be up to 3.7TW while the world consumption is today of ~15TW. In order to collect this energy resource and transform it into useful electricity, wave energy converters (WECs) have been and are developed. Even though more than 150 concepts have been developed until now, none has shown performance competitive with other types of energy converters like for example offshore wind turbines. Heaving and pitching motion based WECs can be classified in different categories which form the big majority of concepts developed until now. The general idea is to place a resonator in the water and convert the oscillating motion into electricity. That type of resonators has a narrow frequency response. Ocean waves, on the other hand, have a very wide frequency range. Heaving and pitching buoys are thus not adapted to the broadband source of energy, as they are only efficient in harvesting energy from the waves around their resonance frequency. In order to increase the power yield of that kind of WEC thus reducing their cost, passive and active control schemes have been tested and implemented already for many different concepts of WEC. Passive control techniques are characterised by an implementation that does not require external energy source to control the WEC, while active control enables the system to adapt to the particular wave conditions by actively feeding energy to the system. Active control techniques can increase significantly the efficiency of WECs compared to passive control but are usually too expensive to be implemented; their implementation and maintenance cost counter-balances the increase in harvested energy. Passive control techniques are more interesting in terms of reliability, cost, and maintenance, but they are still not efficient enough to reduce the cost of energy (CoE) of wave energy converters and make wave energy competitive with the offshore wind industry. A preferred approach for increasing the bandwidth of the resonators would be to find a mechanical solution. A buoy floating in water can be approximated by a conventional mass-spring-damper system. To increase the bandwidth one can either increase the damping or reduce the mass and/or the stiffness of the system. Negative spring or stiffness mechanisms have been successfully used in vibration isolation system to greatly enlarge the frequency band for effective vibration isolation, but surprisingly it has never been applied to WECs even though the physical model behind the two systems is identical.

This project worked towards the reduction of the cost of energy of wave energy converters by coupling to the wave energy devices a negative spring assembly that can enlarge the frequency response, and at the same time increase the power absorption of heaving and pitching based wave energy converters, thus avoiding having to feed energy to the system via active control. The concept of negative spring mechanism already had been successfully used in vibration isolation system to greatly enlarge the frequency band for effective vibration isolation, but surprisingly it had never been applied to wave energy converters even though the physical model behind the two systems is identical. Preliminary numerical study, done by one of the project partners before the project started, showed enhancement of the bandwidth of the power response of a wave energy converter with the negative spring assembly.

Based on this initial hypothesis, we investigated further the negative spring assembly also named WaveSpring. Wavestar was chosen as one of the partners for this project, as the WaveSpring is well suited for point absorber type of wave energy converters. Furthermore, the Department of Civil Engineering at Aalborg University has developed a 1:20 Wavestar model equipped with an electrical linear motor actuator which is the ideal platform to perform a detailed study of the effect of the WaveSpring. The actuator acts as machinery where the damping can be controlled through Simulink. In this way the damping coefficient can be adjusted for the different sea states chosen. The WaveSpring was mounted in parallel with the actuator. The WaveSpring gives the possibility of reducing the mass of the buoy, thus reducing the amount of material of the final device. The study of the gain in harvested power as a function of ballast of the float was also performed. A mathematical model was developed for the WaveStar system, including the WaveSpring component and experimental results were used to validate it. The experimental campaign was performed at the Deep Water Wave basin at Department of Civil Engineering, Aalborg University. The laboratory measurements show how the WaveSpring mechanism influences both amplitude and phase responses, and how it causes an increase in power absorption when the waves are longer than the resonance period of the system. Relative absorption width of up to about 1.4 was measured in the laboratory for regular waves, and up to 0.75 in irregular waves even without optimisation of the machinery damping. The mathematical model was made with modelling options for several of the loads applying on the system. A fairly good correspondence was obtained between laboratory measurements and simulations, even with quite rough modelling assumptions like linear hydrostatic stiffness with saturation and Coulomb friction. Further refinement of the model would require more accurate laboratory measurements. In future modelling it may, however, be a good idea to use a hydrodynamic model that includes the a heave, surge, and pitch motion of the buoy rather than the current one-degree-of-freedom rotation about the pivot A. This would reduce uncertainty and possibly give a better representation of non-linearities coming from the angular motion.

The WaveSpring was also tested on pitching buoy. A Weptos test bench at the Department of Civil Engineering developed in a previous project was used to test the WaveSpring on a pitching buoy. A single rotor was coupled to a rotational generator and the damping on the system was regulated through a PLC control system. The setup was tested in the deep water wave basin at the Department of Civil Engineering, Aalborg University, where the WaveSpring component was installed in parallel with the power take-off system. Several stiffnesses for the WaveSpring were tested in both regular and irregular wave conditions, and the machinery damping coefficient was optimised for the four different sea states chosen. Unloaded tests and decay tests were also performed with and without the WaveSpring. One key issue of those tests at this scale is friction, which would not be as important at full scale. The friction was measured and analysed carefully in order to retrieve the true effect of the WaveSpring. The enhancement factor was positive for all four sea states, but a more significant effect was observed for the three higher wave period sea states with an enhancement factor of 27% only looking at the upward motion of the rotor. A simple model was developed where a transfer function of the system with and without the WaveSpring was obtained from experimental data from both decay and unloaded tests. The model shows general agreement with experimental data, but further development of the model, like inclusion of non-linear stiffness and friction, would be needed to grasp the complete behaviour of the system.

The last device to be tested was a bottom fixed heaving buoy, which resembles the CorPower wave energy converter device. For this part of the project, a test bench needed to be built and this brought some extra challenges to the project. The system built was a light spherical buoy attached to a rope. The rope links the floating buoy to a linear actuator through a pulley fixed at the bottom of the basin. Different models of linear actuators were tested to try to obtain a stable controller for the system. After several experimental campaigns in the laboratory, it was concluded that the system as it was, was unstable and therefor no stable configuration for the controller could be found with the system. A mathematical model was developed for the heaving buoy system. The model takes into account surge, heave, and pitching motions for the buoy, as well as mooring line compliance and pulley friction. The WaveSpring unit is modelled as a combination of friction and negative stiffness. The model shows the power enhancement possible with the WaveSpring, but as it has not been calibrated and validated with experimental data, the extent to which the power can be enhance with the WaveSpring system is not verified.

Several other schemes exist to improve the performances of wave energy converter. A sub-class of those schemes is called active control. Generally speaking, control algorithm can be used to increase the revenue of the project by converting more energy on a yearly base, but also to reduce the capital expenditure by constraining the displacement, velocity or force on the PTO. The particularity of active controllers is that for some fraction of the wave cycle some energy is fed into the oscillating body, which can lead to an increase in the efficiency of the device over a wide spectrum of sea states. In 2007, model predictive control (MPC) has been introduced into the wave energy sector, while few years after in 2011 a conspicuous number of researches were published over the topic. The concept of MPC has been introduced in process engineering in 1983, and it has been extensively used over the last decades in several different fields, such as refineries, oil recovery, etc. The main limitation of the method is the computational burden introduced to calculate the optimal control trajectory at any given time instance. In the project, the aim of this work package was to combine the WaveSpring technology with MPC on the WaveStar test bench. The MPC algorithm was first digitally implemented successfully in a Simulink® model of the WaveStar wave energy converter. It was first benchmarked against other type of active controller and the conclusion was that the MPC is the best alternative from an economic perspective for a single degree of freedom wave energy converter of the point absorber type. The investigation of the influence of the prediction algorithm on the performance of the MPC and a comparison of the results with an ideal model with full knowledge of the future loads were done. The results are reported in terms of absorbed power, cross section area of specific details and cost of energy. The analysis showed that the MPC can handle a large error in the prediction methods, and when the error becomes too large, the MPC revert to a simple passive controller. After this study, the MPC algorithm was implemented in the laboratory model of the WaveStar, where Simulink® is used to control the model and acquire data. To quantify the performance of the MPC controller, the MPC controller was compared with another reactive controller (PI controller) and a passive controller. The average power performance of the three controllers for three different sea states showed higher values for the MPC controller. The following step was to implement the MPC controller for the WaveStar system coupled with the WaveSpring. As the efficiency model for the WaveStar coupled to the WaveSpring model is highly non-linear, its inclusion into the MPC formulation is not straightforward. Some solutions exist for this type of system and their implementation were tempted without converging to a solution for the whole system. Further work is needed to solve the problem.

Many of the most advanced technologies in the field of wave energy are based on heaving and pitching buoys. This includes PELAMIS, WEPTOS, WaveStar, PowerBuoy, Seabased, etc. These are all potential beneficiaries of the WaveSpring technology. The CorPower wave energy converter which is currently testing at EMEC is equipped with a WaveSpring mechanism. Results from the test period are still pending. Nevertheless the results of the project show that a substantial reduction of the cost of energy of all the above-mentioned wave energy converters. This opens up further project opportunities. The devices tested in the project were all laboratory scaled models. One of the obvious continuations of this project is to test a WaveSpring mechanism on the Weptos Prototype, tested in 2017 in Lillebælt. The WaveSpring mechanism could therefore be tested at larger scale, where friction is not as critical, obtaining this way a real value in terms of cost of energy.

1.4 Project objectives

The main objective of the project was to test and prove that the WaveSpring mechanism could improve the performance in terms of absorbed power for different types of wave energy converters.

The first device to be tested and validated on was the WaveStar test bench at the Department of Civil Engineering, Aalborg University. The preparation and the test went as planned. The test bench has been tested and used many times, including the Simulink® code to control the model and acquire data, and the preparation involved fitting the WaveSpring into the existing setup with components that would reduce the friction as much as possible and producing a list of test runs. The tests went as planned and the analysis of the data was done together with the development of the mathematical model. One of the risks in this part of the project was that the tests would show that the WaveSpring does not enhance the absorbed power of the device. This turned out to not be the case. Another risk for this part of the project was that WaveStar would quit before the end of project. WaveStar close down and stopped all their activities on the 15th of April 2016. Fortunately for the project, the tests regarding the device were already completed and since the laboratory test bench was AAU property, further tests could have been performed.

The second device, the WaveSpring mechanism was tested on, was a pitching buoy that resembles one of the rotors of the Weptos wave energy converter. The setup used was a laboratory test bench that was developed by a former employee at AAU during another project. Very little documentation on the setup was to be found. One of the risks for this part of the project was to setup the laboratory test bench, to have it functioning and to develop a Simulink® interface to acquire and control the model. To sum it up, the main risk was related to the needed time to perform the laboratory tests. Again for this device, there was the risk that the WaveSpring mechanism would show any improvement of the absorbed power. In order to mitigate the risk a Master student visiting the research group was affiliate to the project. The tests were performed in the laboratory at the Department of Civil Engineering without extra problem than what laboratory tests imply. The setup was successfully installed and coupled to Simulink® and the tests showed enhancement of absorbed power with the WaveSpring mechanism.

The last device to be tested was a heaving buoy which resembles the CorPower wave energy converter. For this part of the project, a complete setup needed to be built according to parameters chosen based on a mathematical model. Several risks were associated with this part of the project. First, building a laboratory model that function, without excess of friction that would otherwise render the setup unusable, was a risk in itself. This particular risk was underestimated in the project both in terms of time and equipment. The initial equipment originally chosen to be used for the setup was not suited, and an extra LinMot controller with advanced functionalities was purchased. A lot of time was spent on rendering the setup functional, lowering losses and adjusting the force control of the setup. The force control integrated in the LinMot controller is a PID controller with limited functionalities. Since it was not possible to reach a stable controller by adjusting the possible parameters, the force controller was move in the Simulink® code where a current signal was sent to the actuator instead, i.e. bypassing this way the LinMot controller. This again required some extra time as expertise needed to be acquired. The Simulink embedded was successfully implemented, but at the same time, the setup for the heaving buoy was found to be highly unstable. Resonance frequency for pitch and surge motion were found to interfere with the heaving motion. This rendered the setup as it was unusable. Further design, numerical modelling analysis and model modification were needed, but no time was left in the project. Therefore, the power enhancement property of the WaveSpring mechanism could not be proven.

The last part of the project was related to the development of an active control algorithm in combination with the WaveSpring mechanism on the WaveStar laboratory test bench. This part of the project had two risks associated with it. First, the difficulty of implementing the algorithm was unknown and secondly, it was unclear if by combining the active control algorithm with the WaveSpring mechanism that an enhancement of the absorbed power would be achieved. The first risk was underestimated. It is worth mentioning that the problem encountered has not been solved in the literature for wave energy conversion and would require significant manpower, i.e. PhD project, to solve it. Nevertheless, some progression was achieved for the active control algorithm, but as the implementation was not successful, the WaveSpring mechanism effect with the algorithm could not be tested.

It is important to mention that during the course of the project, the department moved twice and there was an important period for which the laboratory was unavailable. This resulted in a request for delaying the end of the project that was granted by EUDP.

1.5 Project results and dissemination of results

As this project was a research-oriented project, the results have been disseminated through journal articles, conference participation, and meetings where relevant stakeholders for wave energy were present. The project did not contain commercial milestones.

The only commercial partner for the project was WaveStar and unfortunately, they decided to stop their activities due to lack of investment to pursue planned projects. This means that the very promising results obtained with the laboratory model of the WaveStar device could not be further transferred to a full scale device, that could have led to increase turnover for this partner.

Even though some of the objectives for the project were not met, the overall results of the project show that the WaveSpring mechanism is a promising technology for enhancement of power absorption for several types of wave energy converter. This difference could help many developers in bringing their cost of energy lower enough to reach entry cost for different market potentials.

The table below contains a list of the dissemination material generated through this research project:

Type of dissemination	*Title*
Journal article	"Physical and mathematical modelling of a wave energy converter equipped with a negative spring mechanisn for phase control", A. Tetu, F. Ferri, M.B. Kramer, J. Hals, will be submitted shortly to *Energies*.
Conference participation	"Practical performances of MPC for wave energy converters", F. Ferri, A. Tetu, J. Hals, Progress in Renewable Energies Offshore: proceedings of renew 2016, 2nd international conference on renewable energies offshore. ed. / C. Guedes Soares. Croydon : CRC Press, 2016. p. 453-462.
	"Influence of the excitation force estimator methodology within a predictive controller framework on the overall cost of energy minimisation of a wave energy converter". F. Ferri, S. Ambühl, J. P. Kofoed, Computational Methods in Marine Engineering VI. ed. / Francesco Salvatore; Riccardo Broglia; Roberto Muscari. Barcelona: International Center for Numerical Methods in Engineering, 2015.
	Effect of a negative stiffness mechanism on the performance of the WEPTOS rotors. S. Peretta, P. Ruol, L. Martinelli, A. Tetu, J.P. Kofoed. MARINE 2015: Computational Methods in Marine Engineering VI. ed. / R. Muscari; R. Broglia; F. Salvatore. Vol. 6 CNR, 2015. p. 58-72.
Stakeholders meetings	Partnerskab for bølgekraft møde, Esbjerg, November 7, 2017.
	WEIB 2017, Copenhagen, March 9 2017.
	Partnerskab for bølgekraft møde, Aalborg, November 29, 2016.
	WEIB 2016, Hanstholm, May 3 2016
	Partnerskab for bølgekraft møde, Thisted, September 14, 2015.
Reports	"Model predictive controller in wave energy theory and application", F. Ferri, DCE Technical Report No. 240.
	"Laboratory experiments on a Wave Star model equipped with WaveSpring phase enhancement", J. Hals, M. Kramer, A. Tetu, F. Ferri.
	"Laboratory experiments on a heaving buoy laboratory model equipped with WaveSpring phase enhancement", J. Hals, A. Tetu, F. Ferri.

	"Laboratory experiments on a Weptos rotor laboratory model equipped with WaveSpring phase enhancement", G. Zorzato, A. Tetu.

1.6 Utilization of project results

As this project was a research-oriented proof of concept project, the results cannot be used straightforwardly. One of the obvious beneficiaries for this project would have been WaveStar, as the results obtained for the laboratory model for the device showed enhancement of absorbed power. Unfortunately the company stopped their activities.

The project, however, straightened collaboration with former NTNU employee Jørgen Hals, now employed at CorPower. Initial discussions have started in order to apply for the next step project in order to test the WaveSpring mechanism on the Weptos wave energy converter as the results in the laboratory showed significant enhancement of the absorbed power. The results from the project inspired part of a bigger application that is currently being written and that will be submitted to the Grand Solutions call in August 2018 from the Innovation Found Denmark.

The results from the project are contributing to realizing energy policy objectives by lowering the cost of energy for wave energy, leading to possible inclusion of more renewable energy in the energy mix. This is also in line with the strategy for wave power in Denmark (published in June 2012) developed by the Danish Partnership for Wave Energy. The Danish Partnership was formed in 2010, bringing together all key stakeholders and with the overall mandate of formulating a renewed strategy for Danish wave power. The current project builds directly on this, as the project addresses the development of PTO technology which will be applicable across different wave power concepts, thus increasing impact and mitigating risks of funding wave power R&D projects. The European Commission has recently released a working document on the action needed to deliver on the potential of ocean energy in European seas and oceans by 2020 and beyond. The results from the project are directly in line with the objectives mentioned in the EU document as it has worked towards reducing the gap between research and the market by reducing the cost of energy of wave energy converters.

The results of the project have been disseminated through a series of dissemination activities, as listed in 1.5. It is important to note that the results were presented several times to relevant Danish stakeholders in order to increase awareness to the possibility of using the WaveSpring mechanism to enhance the absorbed power and thus lowering the cost of energy. To these stakeholders meetings, other institutions like DTU, DHI, and Offshoreenergy.dk were present.

It is important to note that the project resulted in strengthening the high international level of expertise for Denmark in the field of wave energy.

1.7 Project conclusion and perspective

The motivation for this project has been the vision that the partners together could help the wave energy sector, leading to more renewable energy contributing to the global and Danish energy mix. The results from the project have brought wave energy closer to this ultimate vision as significant enhancement in power absorption was observed in laboratory model test equipped with the WaveSpring mechanism. As this technology has shown to work for different wave energy converters, the WaveSpring mechanism is directly linked to a reduction in cost of energy for wave energy.

The results from this project have added to the efforts of Wave Energy Research Group to develop and standardise the wave energy sector so it becomes more applicable for all WEC developers. This project has facilitated further the close relationship that the Wave Energy Research has with WEC developers. Furthermore, the project has increased the competences within the group and strengthened its position on the national and international level.

Finally, further projects with the WaveSpring mechanism technology are planned where the technology will be coupled to Danish concepts at larger scale with big hopes of reducing the cost of energy of the devices, which will ultimately help the growth of the sector in Denmark and create job opportunities in the Danish market.

Annex

The relevant documents have been listed in section 1.5 and are or will soon be made available through http://vbn.aau.dk/ website from Aalborg University.