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The WETFEET Project – A disruptive approach to wave energy

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Abstract— **The H2020 funded WETFEET project started from the in-depth understanding of the main constraints that have been slowing down the development of wave energy to propose, study and develop a set of technology solutions ('breakthroughs') to address these constraints. These breakthroughs were studied having as a reference two wave energy concepts: the OWC (Oscillating Water Column) and the Symphony. The main avenues of research in the project were: 1) Survivability breakthrough via device submergence under storm conditions; 2) O&M (operation and maintenance) breakthrough via continuous submergence and adaption of components and strategies; 3) PTO (power take-off) breakthrough via the development of new materials for submerged polymeric PTO and the analysis and development of innovative electro-mechanic solutions; 4) Array breakthrough via sharing of mooring and electrical connections between nearby devices, as well as integral approach to device interaction and compact aggregates; 5) Increased device performance via the practical implementation and functionality of a negative spring for an OWC. The paper summarizes the scope of the project and the comprehensive methodological framework that was developed for the evaluation of the potential benefits of the breakthroughs, relying on the comparison with reference cases with no integration of breakthroughs. The main results and conclusions are presented. In general, the implementation of the breakthroughs revealed improvements in the LCOE (levelized cost of energy – the main metrics considered in the methodology). Shared moorings shown the most promising results, with LCOE reductions in the order of 20-25%.**

Keywords—**breakthroughs, submergence under storm conditions, sharing of mooring connections between devices, negative spring**

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I. INTRODUCTION

AFTER seemingly significant developments over the past decade, which witnessed the deployment of a few prototypes at sea, progress in the wave energy sector is showing signs of not having lived up to expectations. Former key players have abandoned the field, whereas a few new-comers are being attracted to it. With a view to clarify the issues that need to be addressed in order to put the development of this important energy source (back) on track, both in Europe and beyond, the following issues have been identified as major obstacles to the desired success:

i. Reliability of technical components, particularly concerning the PTO system;
ii. Survivability of overall system (moorings, geometry, operational philosophy);
iii. The long, complex and cost-intensive path towards a marketable product;
iv. The unclear path towards economic competitiveness, including uncertainty on support mechanisms;
v. The unclear path towards industrial scalability, i.e. farms in the range of hundreds of MW.

Together, issues i to iii have largely contributed to the slowing down of progress to date. Time and cost pressure for development within the scope of the highly competitive energy market has led to conceptual shortcomings being brought to full-scale with limited evaluation of risks and alternatives. These include inadequate materials, equipment or operation philosophies for the complex engineering challenge of wave energy.

In addition, over-optimistic expectations concerning the true harshness of the ocean environment, which seems to have been in general underestimated by developers, investors and policy makers, meant that the challenges of installation, maintenance and operation of stationary objects in the ocean were not taken in the right measure. As a result, devices, and in particular critical elements of the systems, were not sufficiently validated before full-scale deployment.

The unclear path towards industrial scalability is a direct consequence of the large dimensions of the future wave energy farms, as they are currently projected, to attain economic competitiveness. Offshore wind economics has shown that, in order to be cost effective, the installed capacity of farms must be in the 300 to 500 MW range. The rated capacity of wave energy converters (WECs) developed to date or currently being developed is in general below 1 MW, typically requiring mooring lines in the range of 0.5 km and electrical dynamic cables in the range of 0.2 km. Therefore, a 400 MW farm may require a number of WECs in excess of 400, 200 km of mooring lines and 80 km of electrical dynamic cables.

The WETFEET project was designed to develop an in-depth understanding and seek solutions to the above mentioned obstacles and the factors that led to the current status of the wave energy sector. With this in mind, the project proposed and developed a set of technology solutions (i.e. components, systems and processes) to address such constraints, which, in view of their disruptive nature, were taken and classified in the scope of the project as 'breakthrough features'. These breakthroughs were studied having as a reference two wave energy concepts: the OWC (Oscillating Water Column) (Fig. 1) and the Symphony (a variable volume submerged point-absorber) (Fig.2).

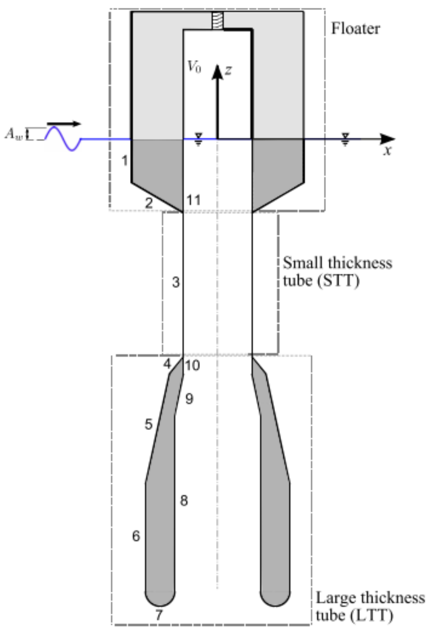

Fig. 1. Schematic representation of the side view of the Oscillating Water Column (OWC) spar buoy used as a reference in the WETFEET project.

The following section presents the breakthroughs which were developed in the scope of WETFEET and the specific wave energy challenges/constraints they address. Section 3 describes the work that was carried out for each of the breakthroughs and summarizes some of the essential results. The overall methodologic framework followed in the project to assess the potential of the breakthroughs in a large-scale deployment scenario as well as the main results are analyzed in Section 4. Final remarks on the outcome of the project, perspectives of future development and the expected impact in the wave energy sector at large are provided in Section 5.

Fig. 2. The Symphony wave energy converter used as a reference in the WETFEET project.

II. WETFEET BREAKTHROUGHS

A. *Survivability breakthrough*

The survivability breakthrough in the WETFEET project was achieved via device submergence under storm conditions. The work carried out included the development and testing of strategies and dedicated components for the submergence of WECs under storm conditions. Solutions for the accommodation of mooring and electric connections were elaborated. The conceptual design of a fully submersible OWC was elaborated, and numerical and laboratory simulations of the submergence procedure and operation with the quantification of device loads and motions was carried out. The work equally comprised the engineering analysis of critical parts and the assessment of cost issues.

B. *O&M (operation and maintenance) breakthrough*

WETFEET's O&M breakthrough was conceptualized as the continuous submergence of a wave energy device (the Symphony) and the associated adaption of components and strategies. The work included the development of fail-safe components for sealing and a removable control cocoon, housing the PTO and all the vital communication systems. A structural membrane for a reduced-scale device was developed and validated via bench-testing, and a simplified working model of the cocoon mob-demob operation was demonstrated in the FloWave tank.

C. *PTO breakthrough*

Innovative alternatives, including materials and components, to the standard wave energy electro-mechanical power take-off equipment (in particular hydraulic PTO configurations) were studied. On average, in the course of one year, PTO mechanisms are subject to up to 3 million cycles under the action of the waves. Based on an in-depth understanding of the significant wear and tear of PTO components and subsequent high failure rates, the project developed the following tasks: (i) preliminary engineering design of Dielectric Elastomer Generators (DEG) for the OWC and the Symphony; (ii) engineering design and bench testing of a novel, efficient and low fatigue tetra-radial air turbine for OWCs; (iii) engineering design and bench testing of a specific water turbine for the Symphony; (iv) working scaled model of a DEG, validated in thorough lab experiments.

D. *Array breakthrough*

Solutions for the sharing of mooring and electrical connections between nearby devices, as well as integral approach to device interaction and compact aggregates were studied. The proposed solutions were compared with independently moored converters. Compact aggregates, conceptually described as multiple reduced motion amplitude devices relatively close to each other, connected to one (semi-)submersible base unit, was one of the studied solutions. Structural, installation, operation and maintenance issues were taken into consideration in the study. The following tasks were conducted: (i) preliminary engineering design of compact aggregates for co-axial OWC devices, with focus on the central connection structure; (ii) numerical simulation of the hydrodynamic interaction between devices for different array layouts; (iii) experimental validation in tank tests; (iv) analysis of the technical, cost, socio-economic and environmental benefits of developing non-rigidly connected devices and compact aggregates sharing mooring connections.

E. *Increased device performance*

The breakthrough on increased device performance in WETFEET entailed the conceptualization, practical implementation and functionality of a negative spring for an OWC. The negative spring concept aims at improving the performance of resonant WECs by tuning their stiffness over a wider range of incoming wave frequencies than just the natural frequency of the structure. Two innovative methods for the application of a hydrodynamic negative spring effect on a OWC spar buoy were explored:

i) The Immersed Varying Volume (IVV) method consists in adding a structure assembled around the lower part of the OWC cylindrical wall, connected to the sea through an opening below, inside of which there is a mass of air trapped on the top part. The motion of the rigid structure (relative to the water) causes the variation of the immersed volume, changing the WEC's dynamics and shifting the resonance frequency to lower values.

ii) The Hydrodynamic Negative Spring (HNS) method involves widening the tube inside the floater of the OWC spar buoy and filling this space with seawater on the downward cycle, and transferring the water back to the sea on the upward cycle (Fig. 3). The buoyancy is thus reduced in the downward cycle since less seawater is displaced, and conversely increased in the upward cycle.

Mathematical models were developed and implemented into numerical codes to solve the systems of equations of both methods. A 1:40 scale model of an OWC spar buoy featuring the HNS concept was wave tank tested.

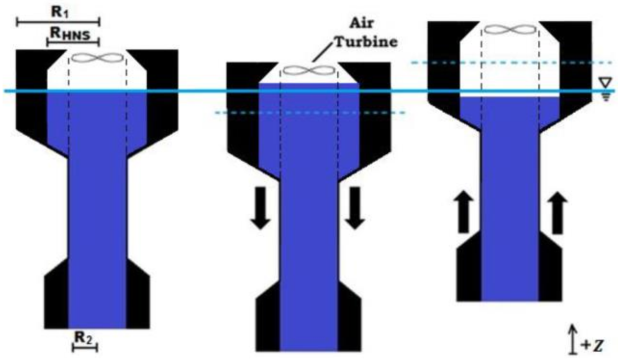

Fig. 3. Illustration of the Hydrodynamic Negative Spring concept. The dashed black lines indicate the dimensions of the unchanged air chamber.

III. METHODOLOGICAL FRAMEWORK

A comprehensive methodology to formulate the concepts and evaluate the true potential and effectiveness of the breakthroughs was developed and implemented throughout the project. During the early stages, the focus was mostly placed on reaching a better understating of the wave energy development constraints and on the conceptual design and development of the breakthroughs to address those constraints. For each of the breakthroughs identified in the previous section, preliminary engineering analysis was carried out and numerical codes/models were developed and applied.

In a later stage, the methodological framework evolved to the definition of design specifications and the confirmation/validation of the initial findings. Detailed engineering analysis was conducted, and the analytical tools and numerical codes developed early in the project were refined. During this stage, physical models and prototypes were built, leading to the experimental validation in bench and tank tests of the final designs of the breakthroughs.

The final stage of the methodology consisted in the assessment, from a cross-cutting standpoint, of the effective potential of the breakthroughs in a large-scale deployment scenario. This encompassed logistics and supply chain analysis for the proposed breakthroughs, integrated techno-economic assessment for large-scale deployment, characterization of environmental impact issues relevant for the large-scale implementation of the breakthroughs, as well as socio-economic impact study focusing on regional capacities and employment related to the proposed breakthroughs. In this stage, the underpinning methodologic framework relied on the comparison of the devices incorporating the breakthroughs with reference case devices with no breakthrough integration. In the case of the OWC, each breakthrough was assessed independently, i.e. the OWC integrating each of the breakthroughs separately was compared with the reference scenario OWC. In the case of the Symphony, due to the nature of the device and of the proposed technology solutions, all the breakthroughs were assessed in a single package, i.e. the Symphony device with all its breakthrough features was compared with the AWS device (the considered reference scenario, in this circumstance).

IV. RESULTS

F. *Survivability breakthrough*

Several strategies have been proposed for the switching of WECs from energy production mode into survival mode. In [1] a review of methods for modelling the loading and dynamic response of WECs and analogue marine structures, such as ships and offshore structures, in large nonlinear waves is provided. The operational philosophy of a relevant class of WECs places them at the sea surface, where they are fully exposed to storms. That is the case of the OWC spar buoy. Device submergence was the survivability strategy proposed as a breakthrough concept in the scope of the WETFEET project.

Given the considerable draft of the OWC spar buoy (see Fig. 1) in relation to the water depth assumed for the reference design case in WETFEET (h = 80 m), the reasonable solution is to bring the OWC spar buoy into a horizontal (or quasi-horizontal) position while being submerged. This allows higher submergence depth to be reached while mitigating the risk of collision with the seabed. In addition, such position will likely prevent the floating structure from having significant motions (particularly heave) in survival conditions, and will minimize the pressure variations along the structure.

Four different submergence depths were taken into consideration: 1/3, 1/2, 2/3 and 3/4 of the water depth h. An inclination of the buoy from its purely horizontal configuration was introduced for both static and dynamic stability reasons (Fig. 4). Numerical analysis using Orcaflex and experimental work carried out in the FloWave tank shown the validity of the considered strategy, which effectively leads to a reduction of the loads on the mooring lines and consequently to a lower risk of breaking.

The submergence tank tests have also shown a general reduction in the excitation forces and moments with increasing water depth. This is an expected result since the hydrodynamic pressure decreases exponentially with depth. It should be noted, however, that a balance between the excitation forces reduction and the increase of static pressure, which may have a relevant impact on the OWC structural design, needs to be reached.

A significant change in the surge excitation force was observed when the OWC spar buoy moved from the upright to the submerged position. The heave excitation force also suffers a considerable net decrease, progressively more significant as the submergence depth increases. The frequencies in which the maximum surge and heave forces are reached decrease with depth. The amplitude of the maximum heave force decreases from 400kN, for water depth d=1/3h, to 108kN, for d=3/4h depth (Fig. 6). Such reduction is likely to have a beneficial impact on the OWC motions in survival mode. For the period used for the extreme hydrodynamic loads computation (i.e. 17.7s), the submerged configurations present a clear advantage, with the heave excitation force decreasing from approx. 744kN at the upright position to 239kN at d=1/3h and 89kN at d=3/4h., as observed in Fig. 6.

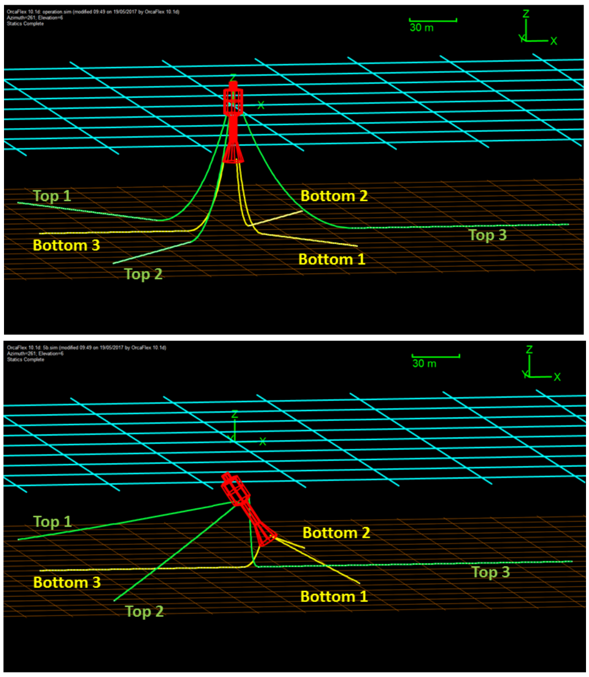

Fig. 4. OWC spar buoy and mooring layout in operational (above) and submerged survival mode (below).

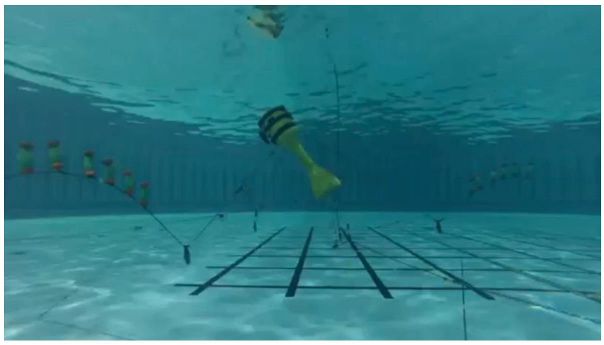
Fig. 5. Survivability testing of a 1:40 OWC spar buoy model in the FloWave tank.

The pitch moment is not significantly reduced from the upright position for the first water depth level (1/3h). The reduction becomes relevant for *d*=1/2*h*. Frequency corresponding to the maximum pitch moment decreases with submergence depth. The ratio between maxima for submerged scenarios and the maximum for the upright position ranges between ~8% for *d*=1/3*h* and 75% for *d*=3/4*h*. This variation shows that a deeper submergence is more suitable in terms of structure integrity in survivability conditions. The optimal solution is a result from the right balance between excitation forces and moments, static pressure, stability and cables disposition.

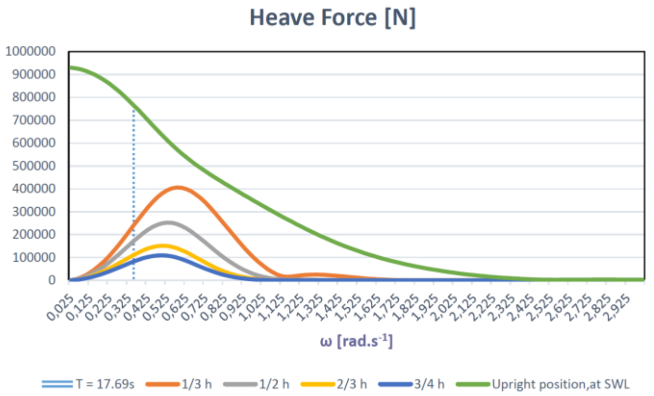

Fig. 6. Heave excitation force for different OWC spar buoy submergence depths.

G. *O&M (operation and maintenance) breakthrough*

The primary function of the structural membrane developed in the scope of the WETFEET project for the Symphony WEC (represented in green in Fig. 7) is the separation between the two main parts of the device. However, its overall functionality encompasses other key aspects:

- Sealing: the membrane acts as a sealing, protecting the internal components from the ocean water and preventing water to flow in the upper part of the hull.
- Bearing: the membrane functions as a bearing in-between the moving hull and the fixed compensation tank. It is important that the membrane centres the hull radially to exclude possible collision between the hull and the compensation tank.
- End stop: the membrane acts as an end stop. The end stop is achieved by narrowing the wall geometry on the inner (static) side of the contact area.

A 1.5 m diameter prototype of the structural membrane (in reality a set of two membranes, one for the upper part and one for the lower part) was produced and tested. The membranes were built in static test tanks to be pressurised. The first bench tests revealed unexpected wrinkles at the folding of the inner diameter to the outer diameter, as a result of the applied fabrication method. Contrary to the expectations, the high internal pressure did not prevent wrinkles to occur. An additional membrane, with the base at the inner diameter and folding outward instead of inward. The improved membrane was built and successfully tested. In parallel, a full engineering study was performed for the full scale and large application of the membranes. Detailed studies of energy losses and resistance, clamping methods and forces, material properties and fatigue were carried out. Fig. 8 shows, from left to right, the mounting of the membrane in the test setup, the membrane at pressure and the wrinkles that occurred.

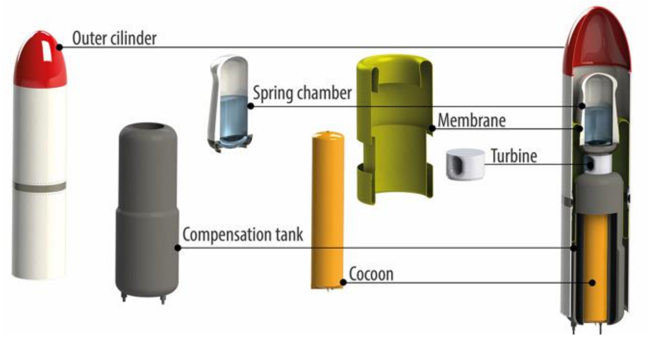

Fig. 7. Exploded view of the Symphony WEC main components.

Fig. 8. Symphony structural membrane 1.5 m prototype.

The control cocoon developed in the scope of WETFEET is designed for submerged devices, where access may be easier due to decreased motions down in the water column as compared with the surface, and where automated service schemes based on ROVs (Remotely Operated Vehicles) or AUVs (Autonomous Underwater Vehicles) are a viable solution. All critical elements (electronics, controls, auxiliary equipment, generator and, on top, the water turbine used as PTO – see below) are placed into this fully insulated cylindrical unit at the bottom of the device (represented in yellow in Fig. 7), from where it can be pulled out when required. The cocoon is intend to be pulled down by an incorporated winch along the taut mooring line in a controlled manner, before it is disconnected from the pulling system and brought on deck or in towing position, requiring only a team of two divers and a light work vessel.

The realisation engineering of the cocoon, its components and its connections (seals to the turbine chamber; potentially underwater electrical connectors to the hull) was carried out. Feasibility assessment focused on the integration of the cocoon into the overall concept via three major avenues:

a) engineering and design, loads and fatigue;

b) design of feasible guidance and docking methodology, allowing the safe removal and reinsertion of the cocoon;
c) demonstration of the feasibility of the Symphony device to keep station without the cocoon (when the cocoon is removed for maintenance).

New aspects on building, fatigue and the interference of the (indirect) forces of the membrane on the outer wall of the cocoon structure were taken into account in the final design, shown in Fig. 9.

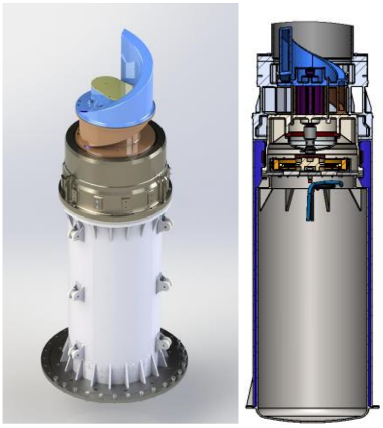

Fig. 9. Symphony control cocoon.

Besides engineering, the complete operation of inserting and removing the cocoon under waves was scale tested in the FloWave tank. The stability of the Symphony device under severe wave conditions with and without the cocoon was confirmed. It was proven that the whole operation can be done remotely using two lines, resorting only to divers to release the locking/keepers to insert and remove the cocoon.

H. *PTO breakthrough*

The potential for cost reduction and the better adaptability to the ocean environment of DEGs place this technology solution as a potential breakthrough for wave energy technology. Two case-studies in which DEG systems are used as PTO in a full-scale OWC spar buoy and in an intermediate scale Symphony WEC (outer diameter 1.5m) were studied and investigated in WETFEET. The DEG architecture chosen for both case studies is the Circular Diaphragm DEG (CD-DEG), studied and tested in previous work ([2] and [3]). Fig. 10 represents the proposed modified designs of the OWC spar buoy and the Symphony device integrating a DEG PTO. In the latter case, the DEG is contacting the inner water volume on the upper side and the sea water on the downer side.

Three different numerical simulations have been run to simulate the behaviour of the OWC spar buoy for different types of material and specific DEG parameters. A plausible architecture for the DEG stacks implementation assumes that each DEG is split into four independent modules (that can be replaced individually in case of failure), with a specific number of layers such that the maximum output voltage is below 50 kV. Basing on preliminary fatigue tests, material exploitation at 70-80% of the break-down field improves the cyclic DEG lifetime up to one order of magnitude, increasing it from 106 to 107 cycles. Maximum applied electric field was thus limited to 80% of the break-down value. Results in this initial stage did not take into account losses due to leakage and conditioning electronics efficiency. Silicone performed significantly better than synthetic rubber as the DE material., thanks to its larger dielectric constant and its lower rigidity, which becomes crucial as the OWC spar buoy PTO is in series with an air volume which tends to absorb part of the deformation induced by the free surface displacement.

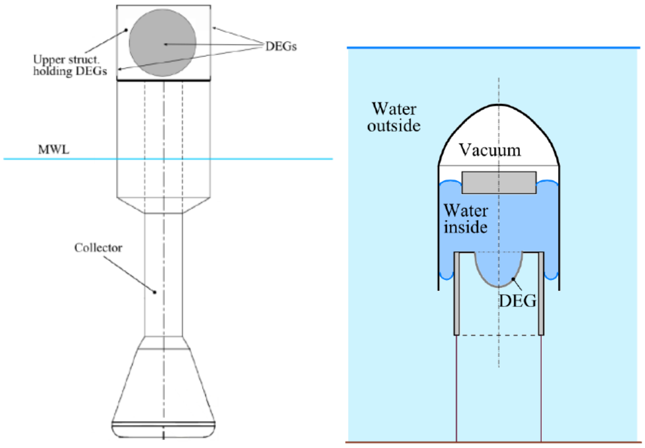

Fig. 10. Modified architectures of the OWC spar buoy (left) and the Symphony device (right) to accommodate a DEG PTO.

For the Symphony, taking into consideration a few architectural assumptions, the relatively large volumes of DE required to withstand high pressure differences and provide appropriate power output, combined with the relatively small diameters imposed by the device's dimensions (outer diameter 1.5m) and kinematics (stroke approximately between -1 and +1 m), imply the need to employ a very thick DEG. This can be achieved by splitting the DEG into a number of independent modules (for easier handling and replacement), eventually separated by water to prevent friction between concurrent surfaces. A coupled DEG-Symphony model has been setup, integrating hydrodynamic, DEG PTO and control sub-models. Simulations were run assuming synthetic rubber as reference DE material, demonstrating that, with the chosen control strategy, sufficient damping can be provided even with limited electric field. The optimal level of damping increases with increasing wave power level.

A test campaign, aiming at validating/refining the simulation models was carried out. The tests employed a novel hardware in the loop (HIL) test bench setup, enabling the testing of DEG-PTO systems in the power range of 1-10W in operational conditions with simulated hydrodynamics. The hydrodynamics of the small scale WEC tested in other tasks of the project was replicated in simulation and an exact replica of the DEG-PTO was built in order to have nearly one-to-one correspondence of the results. By operating the system in HIL, the dynamic response and the power output of the simulated and the real systems were compared. Following these validation experiments, a prototype of silicone-based novel PTO was integrated and a set of tests was run in order to characterize the performance of this new system.

The new tetra-radial air turbine developed in WETFEET was conceived to solve the shortcomings presented by other self-rectifying turbines in OWC applications [4]. The new turbine (see Fig. 11) is based on a pair of conventional radial-inflow rotors mounted on a common shaft, complemented by the corresponding inlet guide vane rows, by a curved-duct manifold arranged circumferentially in a periodic manner and by a two-position axially-moving cylindrical valve. The valve ensures that the air flows alternately through one or the other of the two parts of the tetra-radial turbine, depending on the sign of the pressure head.

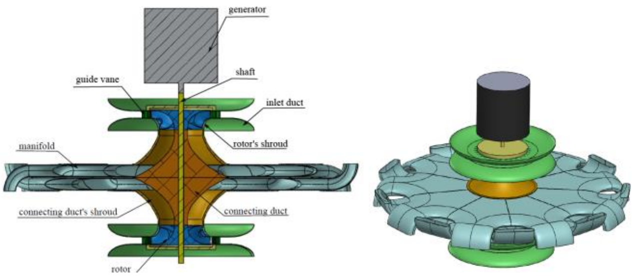

Fig. 11. Schematic (left) and isometric (right) view of the self-rectifying twin-rotor radial flow air turbine.

The turbine was designed using advanced numerical design Computational Fluid Dynamics (CFD) tools. A 2.5kW self-rectifying tetra-radial turbine model was manufactured and assembled at the 13kW IST variable-flow turbine test rig to allow the experimental validation of the turbine aerodynamic design. Turbine performance was demonstrated under time-varying air-flow, simulating regular and irregular wave conditions. The advanced CFD design tools were thus experimentally validated.

The efficiency of the twin-rotor turbine was compared with the efficiency of other self-rectifying turbines commonly used in the OWC. Fig. 12 presents the experimental efficiency curves for the twin-rotor turbine, the biplane Wells turbine with intermediate guide-vanes (see [5]) and the axial-flow impulse turbine with pitching guide-vanes (see [6]).

The biplane Wells efficiency curve has a sharp drop, as it is typical the case of this type of turbine. Its maximum efficiency is 62.5%. The maximum efficiency of the impulse turbine is around 60%, slightly below the peak efficiency of the Wells turbine. Unlike the Wells turbine, the efficiency has a smooth decrease when the ratio $\Phi/\Phi_{\eta max}$ increases above unity. The efficiency of the twin-rotor turbine exceeds the efficiency of the other two turbines. Its peak efficiency is 73.9%. Like the impulse turbine, when $\Phi/\Phi_{\eta max}$ increases above unity, the efficiency of the twin-rotor turbine decreases smoothly.

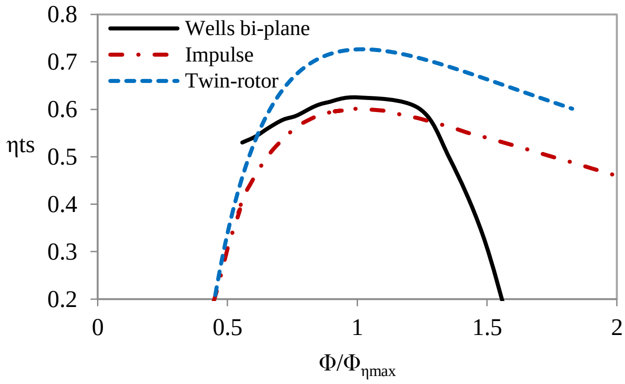

Fig. 12. Efficiency versus flow rate ratio $\Phi/\Phi_{\eta max}$, where subscript η_{max} means maximum efficiency conditions.

A water turbine was the PTO chosen for the Symphony WEC in the course of the project. The design of the turbine for the Symphony faced a major challenge in that the flow speed inside the turbine is bi-directional and irregular. Since there are no off-the-shelf solutions for such operational requirements, a novel water turbine was developed. The focus of the design exercise was to build a prototype for a 1.5 m diameter Symphony and weave considerations for a full-scale device.

As a result of an evaluation exercise, the External Circumferential Piston (ECP) turbine emerged as the most suitable option. The ECP pump presents clear advantages over the lobe turbine (less slip, non-pulsating flow, less critical synchronization requirements). A special challenge in the design was the inlet and outlet geometry of the turbine, to enable a flow as smooth as possible to limit turbulence (heat) losses. Fig. 13 presents the asymmetrical runner ECP turbine design. Bench tests of the prototype gave indications of a good performance.

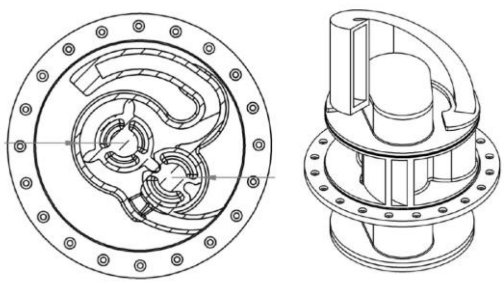

Fig. 13. Design of the External Circumferential Piston (ECP) turbine developed for the Symphony WEC.

I. *Array breakthrough*

Potential configurations of non-rigid inter-moored arrays have been assessed to determine whether cost savings can be achieved with component sharing and what are the implications on survivability, performance, the environment and sea-space utilisation. The OWC spar buoy was chosen as case-study device with a proposed site off Leixões, northwest coast of Portugal, to allow environmental loading to be considered.

Three array layouts were proposed: a linear staggered, a pentagon and a die configuration. The implications of progressively increasing the level of interconnection between the devices was examined. The evaluation of the proposed layouts is summarised in the following:

- array performance was discussed in terms of device interaction;
- survivability examined the array spacing required to prevent collisions based on the array layout and spacing using a simple statics approach;
- line tension under environmental loading was estimated;
- cost was assessed by considering mooring line component costs, electrical cable architecture costs and installation costs;
- environmental impacts were discussed and the sea-space utilisation was quantified;
- experimental and numerical modelling considerations were also discussed.

As a result of the evaluation, the die configuration was selected for the numerical and physical model testing in the subsequent stages of the project. Possible interconnection configurations for the die layout are represented in Fig. 14, which shows the baseline case of the individually moored devices and the three inter-mooring configurations of the devices used.

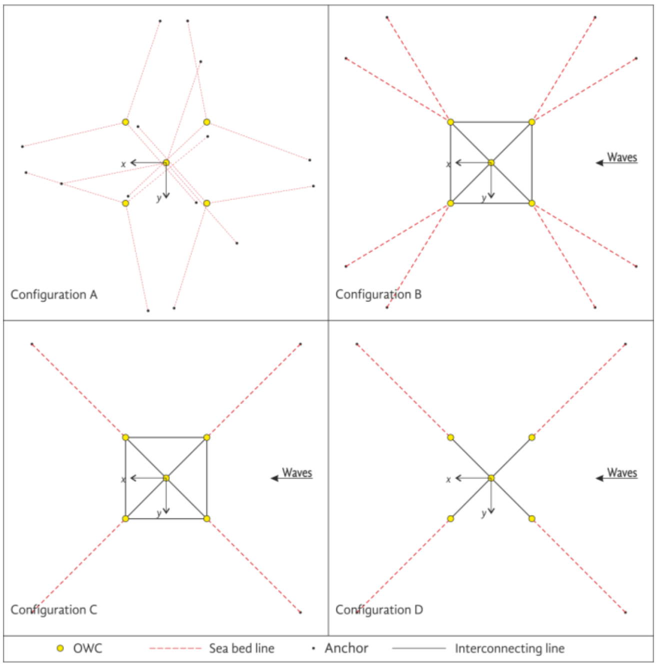

Fig. 14. Interconnection configurations for the die layout in a non-rigid array.

Three inter-mooring configurations were chosen for the non-rigid arrays, as shown in Fig. 14, each with fewer lines than the last. The reduction of the seabed lines not only reduces costs but can also mitigate environmental impacts, both on the benthos and marine life. Survivability and sea-space utilisation have also been considered as part of the comparative evaluation. Even with very conservative collision-avoidance spacing, there may be benefits to inter-mooring devices. In terms of the device spacing, there is a trade-off between power density of the array: closer devices will generate more power per unit area of the seabed, ignoring array effects, but collisions between adjacent devices may be more likely and so may drive up the O&M costs.

Different potential configurations of rigidly inter-moored devices (compact aggregates) were also analysed in terms of loads, motions, risk of collision and performance. The study evaluated the benefits of having rigid inter-connections between devices in order to decrease the cost associated with the installation and also maintenance operations of mooring and electrical cables. Considered parameters and evaluation factors include costs, performance, used seabed area and environmental impact and risk of collision or failure. The device that was selected for the study of the rigid array configuration is the co-axial OWC. An array of five OWCs on a plate was devised.

Wave tank tests of the non-rigid (flexible) array configuration were implemented in two stages. First tests of a single device using a simple catenary mooring as reference case revealed that this was not the best mooring for the motions. New mooring designs with the fewest interconnecting lines/fewest bottom lines were modelled in OrcaFlex (Fig. 15) and these were then implemented in the second stage of the testing programme. Tests of a single OWC, of an array of individually moored OWCs and of the three inter-moored connections represented in Fig. 14 were carried out, for both regular and irregular waves, including extreme sea states. Motions of the devices, loads on the mooring lines and extracted power were measured during the experiments and videos were taken. Wave tank tests of the rigid compact array (single device and full array) considered the same wave conditions as for the flexible arrays.

Results of the wave tank tests were used to validate the numerical models. The validation process compared results from static tests, decay tests and regular and irregular wave tests from the experiments to those generated by the OrcaFlex models. In particular the six-degree of freedom motions and line loads were compared. The numerical models showed good agreement with the experimental results.

In irregular waves, the flexible interconnected arrays presented larger capture with rations (CWRs) than five times the isolated device and the sum of the individually moored array for all sea states tested. For the Leixões site, the individually moored array was estimated to produce 1.4 GWh, whereas the interconnected arrays were estimated to produce ~2.5 GWh annually (an increase of nearly 80%) based on a total available resource of 15 GWh. This increased performance has revealed to be at the expense of large motions and line loads, which may be mitigated with different mooring line designs.

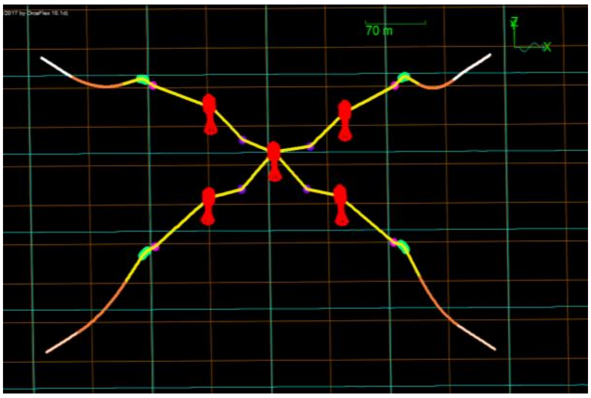

Fig. 15. Flexible array as modelled in OrcaFlex.

The rigid arrays had simpler moorings and the motions and loads were lower than those of the flexible arrays. CWRs were also lower in this case. Further investigation is necessary to discover the effects of the motions on the CWRs and to determine a practical limit of device expansion taking into account wave shadowing, platform motion and structural loads.

J. Increased device performance

Negative springs are unstable systems when deviated from their equilibrium position. This property is key to reducing the stiffness of heaving point absorber WECs and thus significantly improving the energy density performance (e.g. ratios of annual energy production per unit of mass, per unit area or per unit of PTO force).

As described in section II, two different negative spring concepts were explored and numerically studied in WETFEET: i) Immersed Varying Volume (IVV); ii) Hydrodynamic Negative Spring (HNS). Both concepts use hydrostatic effects associated with the shape of the OWC spar structure without requiring additional mechanical or electrical components. It was concluded that, in order to implement the IVV, the air volume required for a resonance frequency shift that covers the total interval of frequencies of interest, [0.66, 1] rad/s, is considerably large - about 1.6e4 m^3. The implementation of a negative spring effect using the IVV has thus proven to be unsuitable for the considered 6 m radius device. The implementation in increased size devices and alternative approaches, such as arrays of small WECs interconnected by air tubes to a common air reservoir, have not been explored in the project but should be subject to future study.

Results from the implementation of the HNS method shown that increasing the effect translates into an extension of the bandwidth and a shift in the response to lower frequencies. In the case of the North Atlantic swell wave systems, where typical wave periods are in the range of 9 – 14 s (0.70 – 0.45 rad/s), an increase in the air chamber radius by less than 60 cm would likely be sufficient to tune the device's response to such typically lower wave frequencies.

Subsequent numerical modelling work, following the experimental validation of the concept in the FloWave tank, confirmed a shift in the resonance frequency to lower values: the resonance frequency of the 9 m diameter floater decreased from 0.775 rad/s to 0.7rad/s, corresponding to a 12 m diameter floater's resonance frequency. However, the implementation of the HNS also resulted in a narrower response bandwidth and a lower displacement amplitude, eventually leading to a poorer annual energy production, taking into account the most representative sea states in the scatter diagram for which the reference OWC spar had been previously optimized.

K. Large-scale deployment assessment

The final stages of the project focused on providing a crosscutting overlook of the different breakthroughs, laying the foundations for a future large-scale deployment scenario. This included logistics and supply chain analysis, integrated techno-economic assessment, characterization of environmental impact issues and socio-economic impact study.

Assessment of logistic requirements focused on mobilization/demobilization, assembly, vessel requirements, installation operation, complexity and feasibility, moorings installation, complexity and feasibility, as well as operation and maintenance. The quantitative evaluation in terms of the impact of the different breakthroughs in the CAPEX, as compared to the reference scenario of an OWC spar buoy without breakthroughs, provided in TABLE I, shown that all the considered breakthroughs reflect positively on the investment costs.

TABLE I
IMPACT OF BREAKTHROUGHS LOGISTICS ON CAPEX

	Reference	*SM*	*SS*	*NS*	*DEG*
	Relative to the reference case (%)				
Total Procurement Logistics	**0%**	-11%	**-3%**	-11%	**-3%**
Total Manufacturing Logistics	**0%**	-13%	**4%**	**0%**	**-3%**
Total Installation Logistics	**0%**	**-7%**	**-10%**	-19%	**0%**
Total Service Logistics	**0%**	-24%	-26%	**9%**	**-9%**
Total	**0%**	**-3%**	**-3%**	**-6%**	**8%**

SM - shared moorings; SS - survivability submergence; NS - negative spring; DEG - dielectric elastomer generators.

Supply chain analysis focusing on components associated with the large-scale deployment of the breakthroughs revealed MRLs in the range 3 to 4. Suitable manufacturers to supply dielectric generators, the structural membrane, the tetra-radial turbine and the water turbine were identified. Manufacturing readiness of the tetra-radial turbine proved to be the most advanced of the manufacturing capabilities assessed, with no result under MRL 4. The water turbine was the breakthrough assessed with the lower manufacturing capabilities overall, with MRL 3 in two risk areas, alongside with the power, sensing and controlling system of the DEG, which reached MRL 3 in 3 risk areas.

The potential benefits of the breakthroughs from the techno-economic standpoint were assessed via a normalized LCOE, in which the LCOE is divided by the LCOE for a reference case with no breakthroughs integrated, considering specific locations. Except for the DEG breakthrough (due to the configuration adopted for the purposes of the project), all variants revealed improvements in relation to the reference case (TABLE II). Flexible shared moorings shown the most promising results, with LCOE reductions in the order of 20-25%. The benefits in this case were two-fold: a reduction of costs due to fewer mooring lines and anchoring points, and an improvement in energy capture resulting from array interactions. The negative spring and the survivability submergence variants presented similar results, with improvements in the LCOE between 5 and 10%, mostly due to a reduction of the initial costs. As regards the survivability submergence, there are also improvements in the O&M costs. There were a few limitations in the analysis, in terms of the underlying available data and the need to further study the breakthroughs to obtain optimal configurations. Nevertheless, the potential of the breakthroughs seems to be unquestionable and it is clear that most of the studied technology solutions deserve an in-depth look in subsequent studies.

TABLE II
IMPACT OF BREAKTHROUGHS LOGISTICS ON CAPEX

		REF	NS	SS	SM	DEG
CAPEX	**Total**	**1,00**	**0,91**	**0,94**	**0,89**	**0,98**
	Device	*1,00*	*0,89*	*0,93*	*0,87*	*0,97*
OPEX	**Total**	**1,00**	**0,90**	**0,97**	**0,89**	**1,23**
	Inspection/Maintenance	*1,00*	*0,89*	*0,97*	*0,88*	*1,29*
AEP	**Farm Capacity Factor**	**1,00**	**1,00**	**1,00**	**1,16**	**0,50**
	Device Capacity Factor	*1,00*	*1,00*	*1,00*	*1,00*	*0,56*
	Availability	*1,00*	*1,00*	*1,00*	*1,00*	*0,90*
LCOE	**Total**	**1,00**	**0,91**	**0,94**	**0,77**	**2,12**
	CAPEX	*1,00*	*0,91*	*0,93*	*0,77*	*1,95*
	OPEX	*1,00*	*0,90*	*0,96*	*0,77*	*2,45*

NS - negative spring; SS - survivability submergence; SM - shared moorings; DEG - dielectric elastomer generators.

Environmental impact assessment (EIA) was equally conducted to identify possible benefits and understand potential barriers to breakthrough development and deployment, to be tackled and mitigated from an early stage of development. Anticipated impacts are, in general, in line with general concerns on the interactions between devices and the marine environment. The shared moorings breakthrough presented clear advantages from an environmental point of view.

The energy and carbon flows, macro-economics and social acceptance associated with a farm of OWC devices, together with 6 different breakthrough variants of the wave farms, were also assessed. Energy and carbon performance was found to be significantly greater than that of fossil fuels, yet lagging behind more established renewable technologies, due to the large amount of material required per unit of electricity generated. Macro-economic effects were found to be significant and wide reaching; positively benefiting all regional economic sectors. It is not expected that the breakthroughs will have significant influence on the social acceptance of the proposed projects, as the existence and nature of the development remains largely unchanged. It is however concluded that, if communicated effectively, all of the breakthroughs have the potential to positively impact social acceptance.

V. CONCLUSIONS

The EU Horizon 2020 WETFEET project proposed and developed a set of breakthrough technology solutions to overcome the stagnation in the development of wave energy aiming to provide a new impetus to technology development within the sector. In general, whereas several of the proposed solutions revealed very promising results, providing firm indications that they are in fact breakthroughs, others revealed the need for further conceptual and engineering work before confirming them as breakthroughs or completely discard them as viable options.

It is anticipated that future research focus will naturally evolve towards those breakthrough technology solutions that have proven and are proving to be more promising in tackling the related constraint. The project was designed to ensure that the new solutions did not bring out new unsolved issues in terms of technical, economic, financial, environmental, policy, regulatory and societal aspects, and that they were developed as much as possible without loss of generality, to guarantee its applicability to other types of WEC. Nonetheless, it should be noted that the scope of WETFEET was to identify/characterize the wave energy sector challenges, propose solutions and initiate its development from TRL 2 to TRL 3/4. Further development of the breakthrough features that will prove to effectively work and of the detailed processes associated to its operation is beyond the scope of the project and should be pursued by the consortium and by technology developers in the aftermath of WETFEET.

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