WETFEET

D2.2 - Report with designs and specifications of a Symphony able to integrate the control cocoon, electro-mechanic PTO, structural membrane and dielectric generators

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Report with designs and specifications of a Symphony able to integrate the control cocoon, electro-mechanic PTO, structural membrane and dielectric generators			
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EXECUTIVE SUMMARY

This report presents Deliverable 2.2 of the WETFEET H2020 project – Report with one or more designs and specifications of a Symphony able to integrate the control cocoon, electro-mechanic PTO, structural membrane and dielectric generators. This and corresponding Deliverable 2.1 for the OWC, form the technical starting point for developing the breakthrough components. This report consists of an introductory description of the proposed breakthroughs in to the Symphony along with a preliminary design analysis of the device.

After the system description of Symphony and the relationship with the breakthrough technologies addressed, the integration of the breakthrough components is individually presented. The marine operations and installation methodolidy is presented. More focussing on the device itself, the dimensions, hydrostatic and wave loads are discussed. Next are the potential challenges descriped and the document ends with conclusions and future work.

The conclusion includes a path toward the realization of the necessary studies to assess more precisely the potential impacts associated with each of the breakthrough. This numerical work will feed deliverable 2.3 and other work packages which are focusing specifically on some of the breakthroughs.

List of Acronyms

AEP	Annual Energy Production
AWS	Archimedes Wave Swing
FEM	Finite Element Method
OWC	Oscillating Water Column
PTO	Power Take-Off
TRL	Technology Readiness Level
TPL	Technology Performance Level
WEC	Wave Energy Converter
WP	Work Package
LCOE	Levelized Cost of Electricity
AEP	Annual Energy Production
CAPEX	Capital Expenditures
OPEX	Operational Expenditures
DEG	Dielectric elastomer generators

1. INTRODUCTION

1.1. Context and motivation

Within the framework of the WETFEET H2020 EU funded project, a set of breakthroughs have been identified to address the obstacles that have been delaying the wave energy sector's progress. Although these breakthroughs are proposed to be integrated into two specific wave energy concepts, they are not limited to these devices. The most efficient and practical way to elaborate on the components is to validate their feasibility by incorporating them into actual devices, whose overall development is driven by dedicated teams.

This integration into specific devices is led by two interacting teams, one of which is led by WavEC and focuses on the OWC spar-buoy, and the other is led by Teamwork and focuses on the submerged heaving device Symphony.

Of the two device types chosen in the WETFEET project, OWC spar-buoy and Symphony, this document focuses on the breakthrough components to be integrated into the latter, as well as on giving an overview of global device functionality and design issues.

Symphony introduction

The Symphony is an evolution from the original Archimedes Wave Swing (AWS) principle, which has been extensively studied for approximately 20 years. As such, Symphony is a classical representative of the class of submerged, pressure differential devices (that shares with the original device its volume variation characteristics). The WETFEET breakthrough technologies discussed in this report apply in general to this class of WEC's.

In 1993 the Dutch company Teamwork Technology started the development of Archimedes Wave Swing (AWS). Model tests were performed in large wave tanks and resulted in improvements and development of new patents. A membrane had already been considered in the design, before the device was further developed as a mass-spring attenuator through variable air volume and air gap, resonating at the wave frequency. In the 1:50-scale model that was extensively tested at HMRC in Ireland a membrane was present, giving good results and leading to the decision to perform a full-scale test on the Northern Portuguese coast.

Here the membrane was left out. As power take-off (PTO), a 2MW rated permanent magnet generator was built and a cable and a land station were developed. In 2004 the full-scale device was submerged to the seabed and the device operated. Analysis showed that the main results are in accordance with the time domain models, resulting in a set of proven models. The trials gave substantial information on how to build and operate systems like this (see Prado *et al*., 2004).

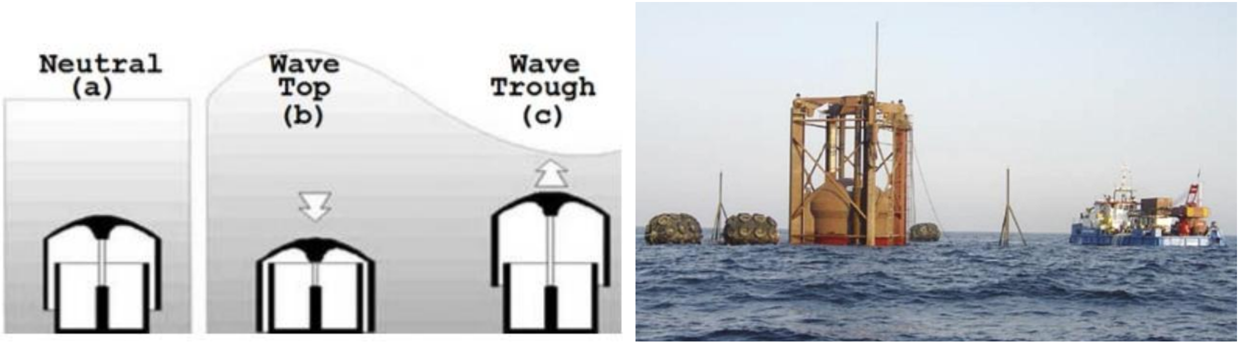


FIGURE 1.1-1: FUNCTIONAL SKETCH (LEFT) AND ARCHIMEDES WAVE SWING 2 MW PILOT PLANT DURING SUBMERGENCE IN NORTHERN PORTUGAL (RIGHT).

In the AWS Pilot plant, the concept of a submerged pressure differential device was realized by a large variable air volume between an inner fixed cylinder connected to the mooring/foundation (in the Pilot plant shown in Figure 1.1-1 mounted on a pontoon), and a moving outer cylinder (floater) driven up and down by the wave motion. The inside contained air with a pressure high enough to counteract the external water pressure and thus providing an open 'air gap' between the two cylinders as interface.

Symphony goes beyond the original AWS concept by adding double membranes and high internal fluid pressure, instead of relying on an open "air gap" and a large variable internal air volume. This removes a significant 'trouble zone' off the original concept and gives the device the same characteristics but in a potentially smaller geometry (lower cost). The spring is linearised via a special patented membrane profile, actually adding a ‘negative spring’ component to the air spring.

Hardly any moving (wearing) parts remain in the device, in particular the turbine/generator and eventually required auxiliary valves. The intention is to place these (critical) components into a removable cocoon that can be removed from the superstructure once installed. This is another innovation with respect to former designs.

The concept is fully scalable. The philosophy behind scaling up Symphony slowly is that the cost of wave power cannot compete with offshore wind or other already developed sources in the short term. Technologies must first be proven and matured with smaller dimensions, and largely supported by public funds and some niche market applications. Once the development and operational risks are limited to small scale, through extensive real sea experience, the increase of the power rating by size, improvement of efficiency and reduction of generation cost will be a more predictable procedure.

1.2. State-of-the art of the Symphony device type

After registering a patent for the roll membrane function for wave energy devices, the Symphony initiators, in WETFEET represented through Teamwork, took up RTD on the development of critical components for a new version of a submerged variable pressure device. The efforts have led to the formulation and outline of technical challenges that must be solved, as well as to new approaches being proposed for wave energy development. These are represented in the WETFEET project. The patents of the original AWS concept are due to expire in 2018. Based on this development, the original concept will be public domain by the end of the WETFEET project.

1.3. Contribution of the Symphony device to WETFEET objectives

Symphony is a submerged variable pressure (SVP) device, and as such - with the exception of its predecessor Archimedes Wave Swing - the only device concept following this principle at present. It builds up on hands-on experience with full-scale sea trials in the open Atlantic Ocean (Northern Portugal), from which very important lessons were learnt. In addition to the marine operations (access issues, redundancy, etc.) and the need to develop a new PTO replacing the linear generator, the substitution of the air gap by a rolling structural membrane in particular turns this device type more attractive for future implementation in the large scale. Furthermore, the need to enable a linearised spring has been identified as important for heaving point absorbers, with respect to controllability and efficiency.

These aspects can be integrated into the device topology of Symphony, which allows for the development of specific components that could turn out to make an important contribution to the breakthrough of wave energy. In addition to the structural membrane, which is connection piece, bearing, end stroke and part of the spring at the same time, also the control cocoon and the new mechanical PTO (water turbine) are focal developments of WETFEET.

2. Symphony SYSTEM DESCRIPTION

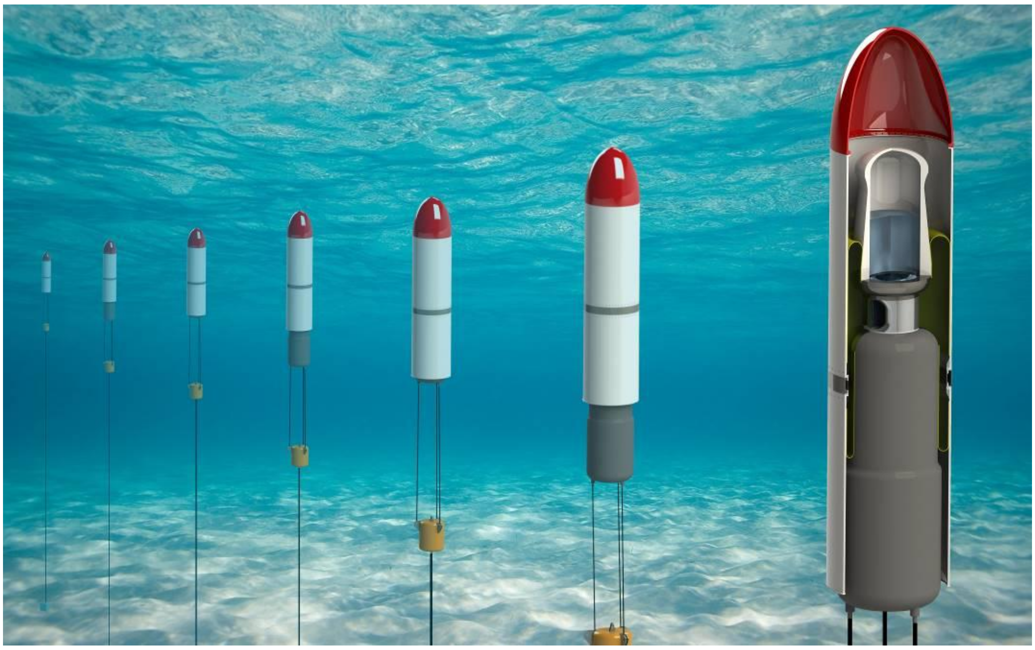


FIGURE 2-1 : ARTIST'S IMPRESSION OF AN ARRAY OF SYMPHONY DEVICES; MOORINGS NOT REPRESENTATIVE (ONLY SHOWING THE TENSION-LEG PART REQUIRED FOR POSITIONING THE DEVICE VERTICALLY IN THE WATER COLUMN). A FUTURE VISION INCLUDES THE POSSIBILITY OF HORIZONTAL UNITS (SEE CHAPTER 3).

2.1. Main components

The Symphony wave energy converter (WEC) basically consists of an inner cylinder vertically fixed in the water column (via mooring lines), and an outer cylinder (floater) that is moving up and down in relation to to the inner cylinder, driven by the alternating wave forces. The cylinders are connected through two membranes (see Figure 2.1-1), each with a different effective surface area., thus making a pressurised internal fluid (most likely water) move within an enclosed volume. The pressurised water volume stabilizes the floater position and makes the enclosed air volume act as a spring. The water movement can also be used directly to drive a turbine as PTO. Although a linear spindle drive has also been considered, the following the system description is based on a water turbine PTO.

Between the internal structure and the floater, there is still a relatively large, variable volume, similar to the Archimedes Wave Swing. However, in Symphony, due to the membrane, this will be conditioned to a near-vacuum stage, in order to improve controllability of the overall system. Air/water compensation tanks located in the inner cylinder are connected to the spring chamber to allow for spring adjustments. All components that are subject to maintenance, as well as the vital controls are located inside a cocoon that is removable under water, while leaving the Symphony on site.

The mooring system and the tidal adjustment connection box are explained in section 2.4.

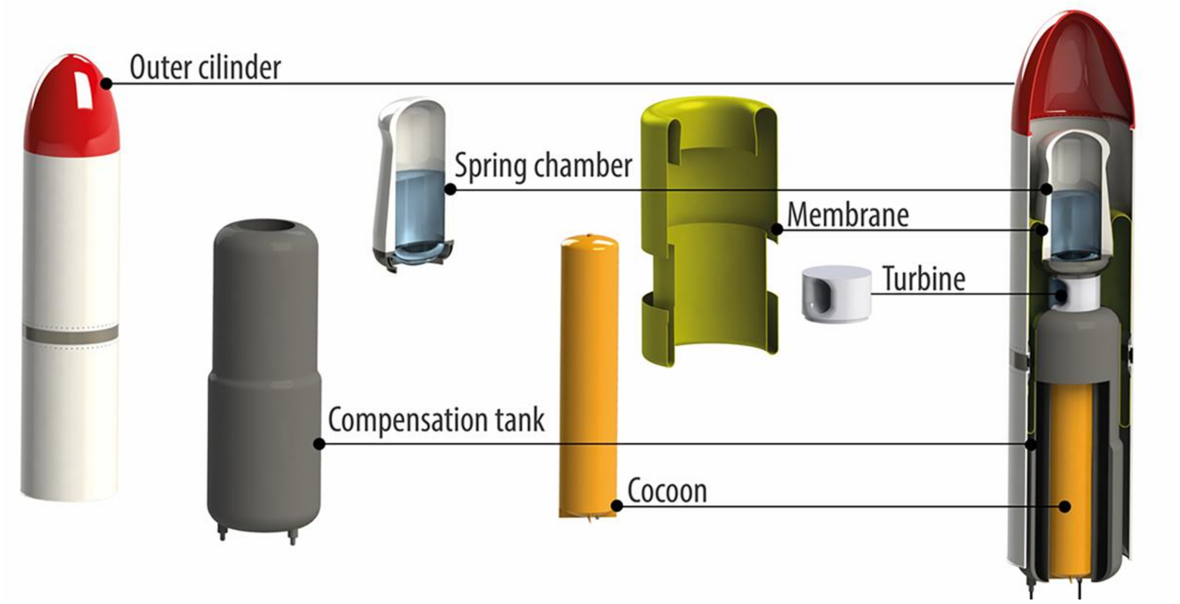


FIGURE 2.1-1 : EXPLODED VIEW OF SYMPHONY MAIN COMPONENTS AND THEIR LOCATION: CROSS-SECTION OF INNER AND OUTER CYLINDER, TURBINE, UPPER AND LOWER MEMBRANES, SPRING CHAMBER PROVIDING THE SHAPED INNER HULL FOR UPPER MEMBRANE, COMPENSATION TANK, COCOON AND OUTER CYLINDER (FLOATER).

2.2. Operating principle and energy conversion chain

The Symphony is a representative of the submerged variable pressure wave energy devices, where the primary mover is located several meters below the mean water surface and driven by the variation of the dynamic wave pressure.

The resonant mass-spring system of the Symphony WEC can be sketched as follows (refer to figure Figure 2.1-1 for components):

The system's mass is defined by the contant mass and the added mass. The constant **mass** of the system is the outer cylinder together with the water inside the membrane. The added mass is the mass added to the symhpony due to the fact that the floater must deflect /move water as it accalerates or decalerates.

The **spring** is realized by using a spring chamber, containing water and air. As the force caused by the wave pushes the outer cylinder down it causes the membrane to roll down. The upper part of the membrane has more volume than the lower part. This makes the volume of the membrane smaller as the outer cylinder is being pushed down. As water is incompressible, the water is squeezed through the turbine, into the spring chamber. The water level inside the spring chamber rises as the water flows into this space. Trapped air in the spring chamber acts like a spring and absorbs energy when being compressed and then gives it back when it expands. as the wave passes by and the force caused by the wave decreases. At a certain point the force on the membrane exceeds the reacting force generated by the waves. This slows down the movement of the outer cylinder and ultimately pushes the it back upwards. Key to this functioning principle is a significant over-pressure in the spring chamber in comparison to the environment.

A mass-spring-system has one or more **dampers**. The damping energy brakes the movement of the spring system. If the system had no damper it could become unstable. The Symphony is submerged in water, and there are two types of dampers: undesirable and desirable.

Undesirable dampers:
- Internal friction caused by friction of moving parts like bearings.

Desirable dampers
- Turbine and generator energy extraction. The turbine extracts energy out of the system to generate an electrical current and to keep the system in a resonant movement with the excitation force.
- End stop dampers: physical dampers that brake the system in severe sea states.

In order to create a **resonant system**, its frequency must be in phase with the wave frequency. The system's frequency is calculated using a time domain model [Kooiman,2015].

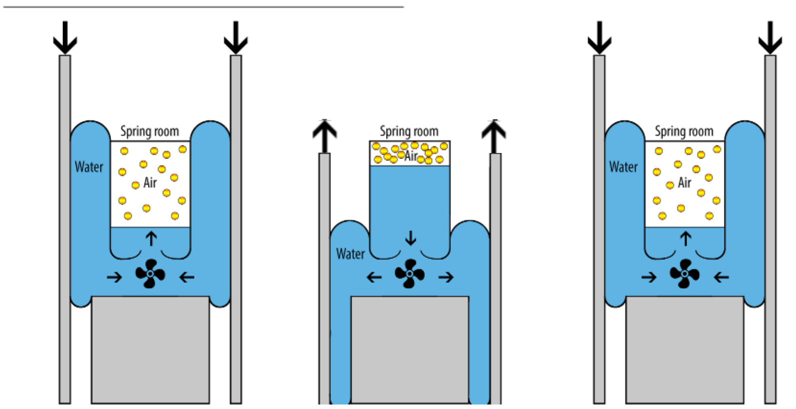


FIGURE 2.2-1 : LEFT: SCHEMATIC VIEW OF POTENTIAL POWER-TAKE-OFF (PTO) APPROACH FOR SYMPHONY: TRANSLATING HEAVE MOTION INTO ROTATIONAL MOTION (WATER-DRIVEN TURBINE) AND WATER VOLUME INTERACTION BETWEEN STRUCTURAL MEMBRANE AND AIR/WATER TANK; RIGHT: BASIC MASS-SPRING SYSTEM OF SYMPHONY: F_W IS THE FORCE FROM WAVE; ω IS THE ANGULAR WAVE FREQUENCY; X IS THE VERTICAL FLOATER POSITION (FROM REFERENCE POINT); m IS THE INERTIA (FLOATER MASS + ADDED MASS); β IS DAMPING (POWER CONVERTED IN PTO + LOSSES,); k IS THE SYSTEM SPRING CONSTANT.

The following sequence sketches the Symphony operation during a wave cycle:

1) System anchored to the ground, wave starts passing over the device, water pushes the outer cylinder down, making it accelerate downwards. The water in the roll-membrane is being pushed through the turbine, which extracts energy from the water flow. Air compresses when water flows in the spring chamber, generating a force on the water inside the spring room.
2) When the wave crest is directly above the top of the floater, the force applied on the outer cylinder is at its maximum. At this point the outer cylinder (floater) is moving downward at its maximum speed with zero acceleration.

3) As the outer cylinder is being pushed down, the increasing resulting force due to the compressed air becomes greater than the force generated by the wave, making the velocity from the movement of the outer cylinder decrease.
4) System at its lowest point. The compressed air reaches its highest pressure of the cycle. At this moment the outer cylinder speed is zero and the upwards acceleration is maximum.
5) The compressed air in the spring chamber creates a force on the water inside the spring room pushing it back to the turbine which extracts energy from the water flow into the roll-membrane.
6) The outer cylinder keeps accelerating upwards until the force of the wave pushing the outer cylinder down and the force of the compressed air pushing the outer cylinder upwards become balanced again. Once this balance is reached, the velocity of the outer cylinder moving upwards reaches its maximum.
7) The outer cylinder slows down as the force generated by the water becomes greater than the force of the compressed air.
8) The acceleration keeps on increasing downwards until it reaches its maximum. At this point the velocity of the outer cylinder is zero.

As a new crest passes, the outer cylinder starts moving downwards again, repeating the cycle.

2.3. Control mechanisms

To ensure the operational sequence as described above, the following items are required for control. A smooth functioning depends on the communication between different complex processes, which are simulated by a time-domain model [Kooiman,2015], and need to be adjusted with real parameters during trial phases. The speed control of the turbine is the dominant parameter, as it can damp the motion according to the incident wave energy. It is controlled to counteract the wave force, by the absorbed power through the generator controlled by power electronics. The right amount of damping must be applied in every instance. This amount can be calculated by the behaviour of the device itself, e.g. by measuring the pressure in the very small amount of air in the vacuum between floater and the pressure tank (this pressure has a direct relationship with the position of the floater). Further pressure sensors are in the membrane and compression chambers and on the outside. Measuring the pressure gives the information of the motion of the device and the wave force acting on the moving body. The control is a constant feedback control. In case of loss of controls, the system is intrinsically safe via the end stop function of the membrane with shaped inner hull (see section 3.1). The following subsystems are required for controlling the Symphony; most are incorporated in the control cocoon (see section 3.2):

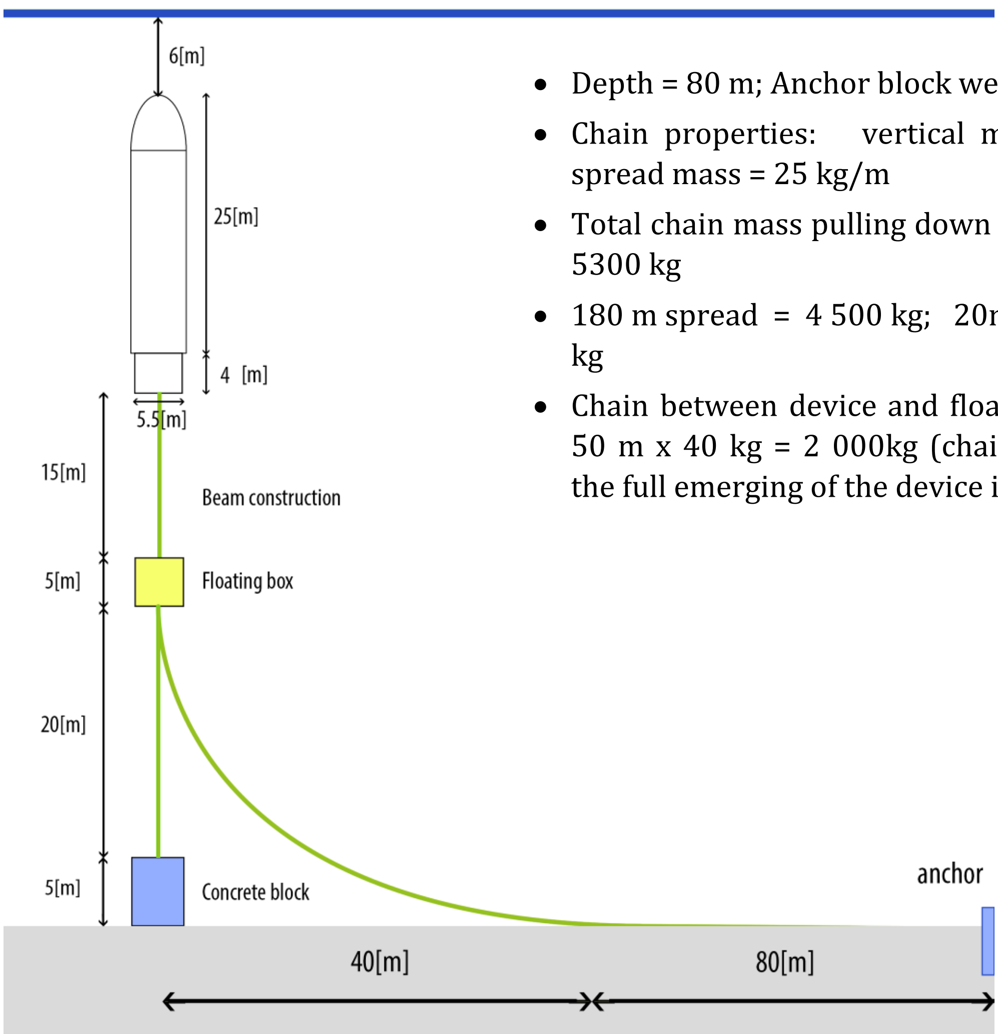
- **Water storage**: for the case of water leaking from the roll-membrane, new water can be supplied from the spare water storage in the core.
- **Compressed air tank/vacuum pump**: if more air pressure is needed in the spring chamber, compressed air can be supplied from the compressed air tank (which can be reversed by a compressor). The compressed pressure might have to be varied during

operation. The vacuum can be regulated, and unexpected or creeping leaks can be corrected using the vacuum pump.

- **PID system**: The PID (proportional–integral–derivative) controller system monitors and controls the generator, and thereby the turbine speed.

2.4. Mooring system

The mooring system for future devices will be especially designed based on prototype experience, outside of the scope of WETFEET. In order to allow for the testing of the WETFEET breakthrough components and the construction of a functional Symphony model for tank testing in a later stage of the project(in the scope of WP3), a preliminary mooring system has been designed (see Figure 2.4-1), consisting of a tension leg for keeping the device vertically in the water column (The floating box is envisaged for tidal adjustments, and placed at a sufficient distance to allow an easy removal of the control cocoon; see section 3.2), and a slack mooring for station keeping. When transposing this tentative mooring design to a future 6m reference device, the following mooring setup results:



- Depth = 80 m; Anchor block weight = 25 000 kg
- Chain properties: vertical mass = 40 kg/m; spread mass = 25 kg/m
- Total chain mass pulling down at floating box = 5300 kg
- 180 m spread = 4 500 kg; 20m vertical = 800 kg
- Chain between device and floating box: length 50 m x 40 kg = 2 000kg (chain accommodates the full emerging of the device if needed.

FIGURE 2.4-1 : INDICATIVE MOORING LAYOUT FOR A 6M SYMPHONY IN 80M DEPTH

3. INTEGRATION OF BREAKTHROUGHS

The main purpose of the initial tasks of WP 2 is to draw up the integration of the target breakthroughs for each device into functional overall systems. The level of detail required corresponds to conceptual design for energy-scale prototypes (representative diameter of 6m), whereas the functional models to be developed in WP 3 are designed for physical integration of a 1.5m diameter structural membrane prototype at a later stage. This design experience has partly flown into the work presented in this deliverable.

The breakthroughs that are part of the Symphony-relevant work programme are: (i) the structural membrane, (ii) the control cocoon for continuous submerged operation, (iii) the dielectric elastomer generators (DEG), (iv) shared mooring systems and (v) a new electro-mechanical PTO.

The DEG and shared moorings are more long-term concepts with dedicated work packages including the interface to other device components and overall integration (WP 5 and WP 6, respectively). The status of work with respect to these breakthrough components is therefore more preliminary, as intermediate results in those WPs can have decisive consequences on the integration. The reference dimension for these items is a serial-produced 6m diameter Symphony WEC. On the other hand, the structural membrane, the electro-mechanic PTO and the control cocoon are the focal aspects of the early-stage Symphony development, and they will be incorporated into the first working prototype (1.5 m diameter), to be built as a follow-up of the WETFEET project. The sections referring to these components therefore describe the basis of work from which WP 3 and WP 4 start.

3.1. Structural membrane

The membrane is the key innovative feature of the Symphony concept, solving the connection between the prime mover and its reference body. It acts as seal to enclose the inner pressure/volume and as bearing for the outer cylinder. In a way the membrane provides the variable volume ‘breathing’ under the waves. The inner volume changes due to the difference in the width in which the upper and lower part of the membrane roll up and down.

As the sleeve (outer cylinder) is being pushed down, the roll membrane starts to roll down. As the membrane rolls down the volume inside the membrane is reduced and forces the water into the spring chamber trough a turbine. As the built-up pressure in the spring chamber forces the water back, it is pushed into the membrane which rolls up with the outer cylinder.

The integration of the membrane is possibly the most relevant innovation for a fully submerged heaving device. Apart from being a complex and demanding task to design the membrane itself (due to the high amount of load cycles and the multiple functions, as it will be seen in WP 3), the geometric vision of using a flexible membrane for connecting two cylinders in relative heave motion with respect to each other, is relatively straight-forward. When considering the functional requirements of such a membrane however, the demands for design and integration become clear; directly or indirectly, the membrane assumes the following functions in the Symphony device:

1) **Sealing**, protecting the internal components from the ocean water and preventing water to flow into the upper part of the hull.
2) **Bearing** in-between the moving hull and the fixed compensation tank and the spring chamber, respectively. It is important that the membrane - supported by the internal water/air pressure - centres the hull circumferentially to exclude possible collision between the hull and the compensation tank.
3) **End stops**; as the device is a resonator the amplitude of its motion can be higher than the amplitude of the exciting wave. If the power is not converted the stroke could increase until the device would be compromised. The end stops need to create a counterforce. By narrowing the internal guiding wall geometry of the upper membrane(see below). The direction of the force will be changed and therefore the movement first braked and then inverted.

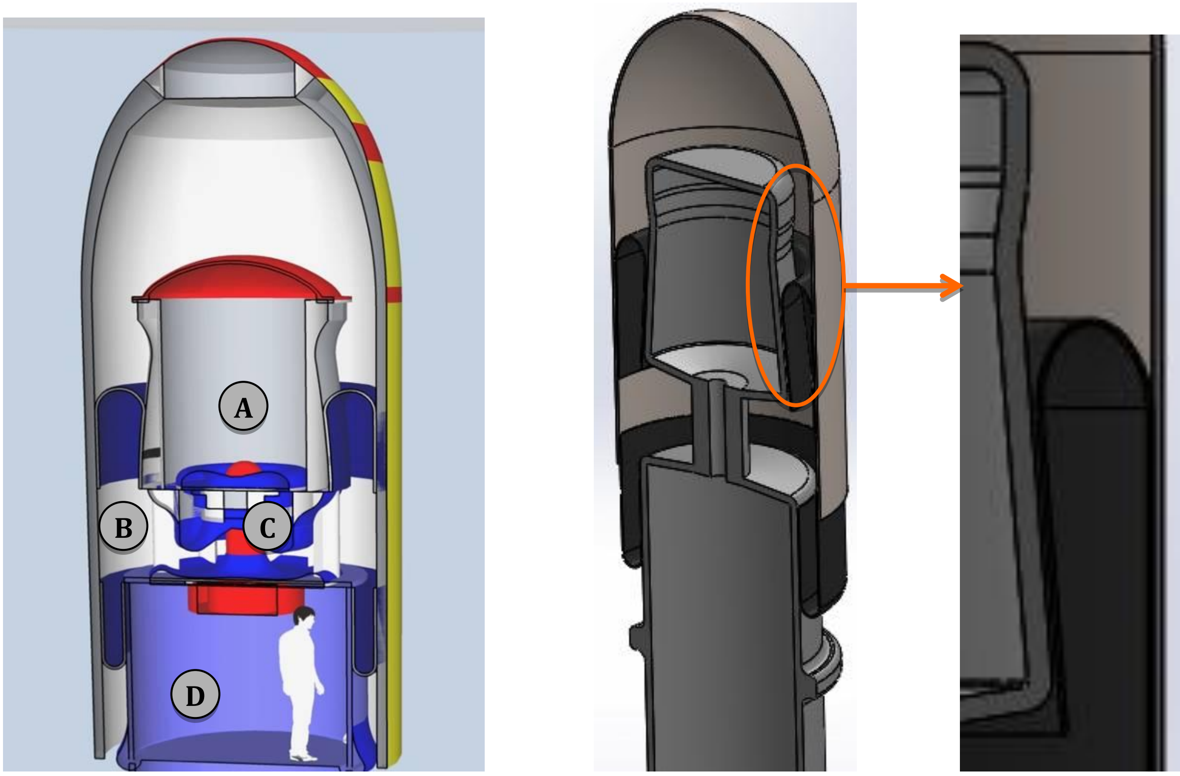


Figure 3.1-1 : Cut-out view of Symphony with key functional components A) Spring (compression) chamber, B) membrane chamber, C) turbine, D) air and water compensation tank room (left). Centre: cut-out view with emphasis on membrane and shaped inner hull. The membrane has an upper part and a lower part. Right: zoom into the upper membrane.

Shaped inner hull.

The third point above mentioned - the shaped inner volume - is an important feature of the device design, vital to provide the end-stop function. However, particular attention must also be paid to the detailed shape in order to ensure the desired characteristics of the mass-spring function. Since the membrane acts as a piston and works against the pressure in the compression chamber (air/water tank), the pressure times the surface of the piston

(membrane) quantifies the force. For optimal, controlled operation this force increases linearly with the displacement of the floater (spring characteristic). The air pressure variation inside the spring chamber is non-linear. The force is then linearised to optimise the efficiency by increasing the upward-facing surface of the upper membrane as the floater moves upwards. In Figure 3.1-1 this can be seen in the shape of the inner cylinder of the upper membrane (outer shape of spring chamber). The dynamic behaviour and controllability of the Symphony device will be very sensitive to the shape of the inner hull and the resulting force differential between upper and lower membranes [Kooiman,2015]. The resulting shape of the membrane to be designed, manufactured and tested in WP 3 has been calculated using the time domain model and the preliminary results are presented in section 5.1.

<u>Centering force of the membrane</u>

A conceptual risk analysis showed that the system might become inefficient or even damaged when horizontal forces associated to the waves cause the outer cylinder to touch the inner structure. To avoid this, the membranes' centering force needs to be sufficiently strong to counteract the extreme sideway forces. Calculations have been conducted to define the system's stiffness (see van Noorloos,2015), to find out if the membrane's centering force is sufficient, and whether the membrane's natural frequency will not become resonant with the frequency of the waves. For the extreme case of centering function of the membrane, the calculations were made for a static situation, for which the core is fixed. In Figure 3.1-2, the top view cut out of the Symphony is visualised where the dark grey line is the outer cylinder and the yellow surface represents the internal components of the device. The outer cylinder is being pushed in the horizontal direction caused by the horizontal forces of thewave. The wave force is acting perpendicularly to the heave direction of the WEC.

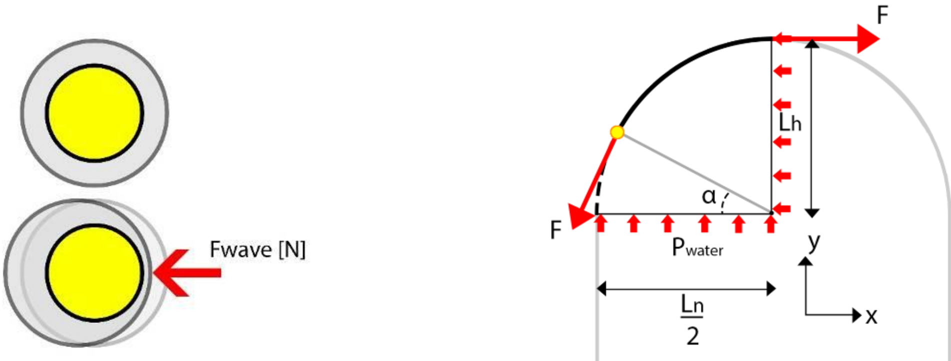


FIGURE 3.1-2: LEFT: TOP VIEW HORIZONTAL MOVEMENT OF THE MEMBRANE. RIGHT: FORCE DIAGRAM ON WHICH THE CENTERING FORCES, AS THEWELL AS UP- AND DOWNWARD FORCES (DRIVING THE FLUID THROUGH THE TURBINE)OF THE MEMBRANE ARE CALCULATED.

The simulations conducted in [van Noorloos,2015] show that the system will not move more than 10 mm when operational, and not more than 12.5 mm in severe conditions when the inner parts of the Symphony are completely fixed. Such displacements will not damage the internal components due to impact. The simulation shows further that the natural frequency of the membrane is not in phase with the typical waves frequency band, therefore the membrane will not be resonant with the waves.

Material choice

An engineering choice with significant importance for future up-scaling plans is the membrane's material, as it needs to have specific characteristics, reasonable costs and long-term availability in large quantities. The latter aspect is important to consider at an early stage, due to the key functions of the membrane for this type of WEC, and the need for substantial testing in controlled environment in the prototype phase. Thus it becomes of great importance to be able to transfer the prototype results into later developments.

The material is subject to a high number of reciprocal load cycles with high pressure/force gradients (internal operating pressure of 10-20 bar(g)). The current concept of the membrane will be made of a soft rubber with integrated aramid fibres placed continuously in the longitudinal direction of the membrane. Aramid has a tensile strength of 3100-3600 MPa and an elongation at break of 1.7% [Nijssen 2013]. The aramid fibres are used in order to give the membrane its strength to hold the high pressure and to prevent strain in lengthwise direction. The soft rubber allows the membrane to change its shape at a minimum strain resistance. A risk analysis had been made in order to find out what the risks of damage to the membrane are (van Noorloos 2015). Among the risks identified are (i) insufficient centering force, (ii) membrane's natural frequency becoming resonant with the waves frequency, (iii) leakage, (iv) vacuum influence due to degassing or leaks, (v) wear & tear, (vi) efficiency loss due to horizontal material strain, and (vii) impact damage at turbine failure or severe conditions.

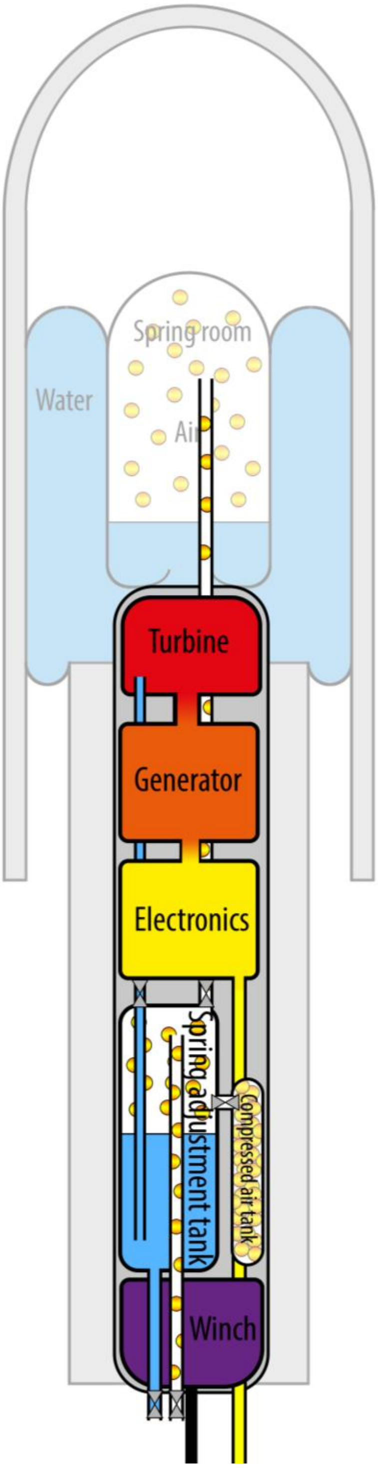
Due to the central importance of the membrane for the overall viability of submerged pressure variation devices, the expert company in the field of polymer solutions, Trelleborg, has been invited into the consortium with the specific task to design, manufacture and build a prototype membrane taken into considerationthe above mentioned risks. Material properties, processing and fixing will be part of the design process in WP 3, whereas the risk of insufficient centering force and the membrane's natural frequency have been part of the preliminary work in this WP, summarised above.

Another important aspect for the integration of the membrane into the device is to account for controllability and accessibility during the assembly. A video sequence has been elaborated to visualise and continuously adapt the membrane integration, as part of the ongoing design process.

3.2. Continuous submergence: the control cocoon

The control cocoon is the second distinctive component of Symphony with respect to the state-of-the-art. Being a permanently submerged device, the access to vital components and controls is on the one hand a special challenge, which on the other hand allows for new approach to access and remove/reconnect such components for maintenance. To ensure this possibility was one of the most important conclusions learnt from the full-scale Archimedes Wave Swing trials, where communication to controls was lost upon deployment, with serious consequences on the further test sequence. Whereas in this case the test programme could be modified to bridge the most relevant gaps, the loss of controls or mal-functioning of components in operation typically requires the removal of the WEC for maintenance on land.

The control cocoon contains the critical parts of the Symphony, and can be removed without transporting the complete device to shore. The cocoon includes the following parts:



- **Turbine**: a custom dual direction turbine will be used to drive the axis of the generator. The turbine is the interface to the static volume of the device, and the most critical part is the sealing between cocoon and internal water volume.
- **Generator**: the axis of the turbine is connected to a permanent magnet generator, which could be used to drive the turbine axis, too. It is sealed in the interior of the cocoon and has no critical interfaces to the outside.
- **Electronics and control system system**: the electronics will be placed in a sealed box, from where the winch (for tidal adjustments), generator and valves of the pressure systems are controlled. This is the core part of the device control, and might be placed closer to the end of the cocoon for easier access. Slight over-pressure is being considered for additional protection. Critical physical interfaces to the outside (unless going through winch).
- **Spring adjustment tank**: this unit is required to integrate the tuning of the air spring. If a limited unwanted pressure drop/raise occurs in the spring chamber due to leakage or temperature changes, the spring adjustment tank is used to compensate. The pressure inside the spring adjustment tank will be the same as the neutral pressure of the spring chamber which is around 15 bars(g). An air connection of the adjustment tank to the spring chamber is another important interface between the cocoon and the static device parts, as well as air and water valves to the outside.
- **Compressed air tank**: a compressed air tank with control valves is placed in the cocoon in pressurize the spring adjustment tank. The pressure inside the compressed air tank will be 100 bar(g).
- **Winch**: for tide compensation and survivability mode under severe sea conditions, a winch unit is placed on the bottom part of the cocoon, which will pull the Symphony down. It will equally be used for maintenance removal of the cocoon. Interfaces to upper part of cocoon and/or outside of device.

FIGURE 3.2-1: SCHEMATIC VIEW OF COCOON HOUSING VITAL COMPONENTS AND CONTROLS OF SYMPHONY

The design challenge for the cocoon, to be addressed in detail in WP3, is to manage on the one hand to stack all components in one unit, and on the other hand to ensure water-tight sealing for the following connections under pressure differentials of up to 20 bar:

- interface cocoon (turbine) <--> water volume between membranes (water)
- interface cocoon (compression tank) <--> spring tank membranes (air)
- interface cocoon (spring adjustment tank) <--> surrounding water body (water & air)
- interface cocoon (winch) <--> surrounding water body (water)
- interface cocoon (electronics box) <--> surrounding water body (water)

The cocoon is realised as a tube withstanding the environmental pressures and some degree of shock loads for assembly of the heavy duty components and handling operations. A major design demand is the ease of dismounting/re-mounting from/into the Symphony. While the most critical parts from the maintenance standpoint are placed inside the cocoon and can be removed, a remaining challenge is to close tightly and securely the gaps that the removal of the cocoon creates.

Valves, seals and connectors for this application are partly custom-made items with special requirements. Also the electrical connection between the cocoon and the stationary power and control cable needs to be designed under this consideration. The design of these interfaces is work in progress with the scope of building a cocoon prototype for the 1.5m Symphony, following the WETFEET project results to be elaborated in WP 3.

3.3. Dielectric elastomer generators (DEG)

The most visionary and long-term innovation, envisaged within WEFEET, for both the spar-buoy OWC and the Symphony, is to replace the planned PTO solutions by Dielectric Elastomer Generators (DEG). The operating principle of a DEG has been conceived less than a decade ago and it is based on a solid-state deformable transducer made of elastic polymers that can convert mechanical energy directly into electricity via the variable-capacitance electrostatic generation principle.

In the context of wave energy harvesting, potential advantages of DEG technology over traditional PTO systems are: direct drive cyclical operation with good energetic efficiency that is almost independent of wave period; easier installation and maintenance; lower costs.

The overall feasibility of energy conversion from waves into electricity employing a DEG-PTO has been demonstrated in the Future Emerging Technologies EU FP7 Project PolyWEC (Pj.Ref. 309139) (the coordinator and one of the key partners in PolyWEC are part of WETFEET's consortium). More specifically, DEGs have been tested in operative condition in scaled laboratory experiments and their concrete potential for integration into wave energy converters has been proven. Small scale prototypes in the Watt-range have shown experimentally verified wave-to-wire energy densities of 0.7 kJ/kg (i.e. energy converted for each cycle by a unit volume of employed dielectric material) and conversion efficiencies of nearly 25%. However the concrete perspective is to increase energy density up 1 kJ/kg and efficiency up to 60-70% in a relative short timeframe by using more efficient materials. For

example, the multinational company WACKER Polymers has recently released a new product that is specifically dedicated to the application of a DEG named Elastosil Film, which is showing extremely promising performances.

However, given that DEGs are still an emerging technology, they have not yet been considered for prototypes in the framework of WETFEET project, but the further development of DEG as future PTO is pursued in a dedicated work package, WP5. The main aim of WP5 is to: 1) conceive and characterize new conducting and dielectric deformable materials (beyond the sole silicone elastomers investigated within the PolyWEC project) that will be pursued to enhance DEG performances, as well as 2) validate their fatigue life and degradation; 3) develop and verify more accurate models that will be employed for the design and control of the system.

However, in order to steer the research toward tangible applications, a study is going to be conducted in order to define DEG-PTO to be integrated into the spar-buoy OWC and the Symphony. An accurate definition of the layout and dimensioning of a possible DEG-PTO to be integrated in such WEC concepts should go through an in-depth hydrodynamic analysis that is not yet available at the current stage of the project. However, it is possible to draw an initial hypothesis of layout through a preliminary analysis based on theoretical considerations and on the results of previous experiments conducted by some of the partners of the consortium. Specifically, the following approach is assumed:

- Converted energy density: the amount of energy that can be converted by a unit of mass of dielectric elastomer in a cycle (i.e., one full oscillation of the DEG) is limited by a set of known boundary conditions such as maximum deformation of the material (in operational conditions) and maximum electrical field that the dielectric can hold. This means that for a given energy output a minimum requirement for the volume of needed materials can be foreseen.
- Power matching at specific frequency: in order to have a preliminary dimensioning of the mass/volume of dielectric material that is needed, it is necessary to specify the peak power of the device and the typical working wave period that is assumed.
- Considerations on manufacturing and deployment: based on general consideration on manufacturing, transportation and installation an initial layout can be defined.

Figure 3.3-11 presents the scheme of such approach. Once the peak power is established, it is possible to estimate the minimum quantity of material that has to be employed to guarantee that such peak power target is reached.

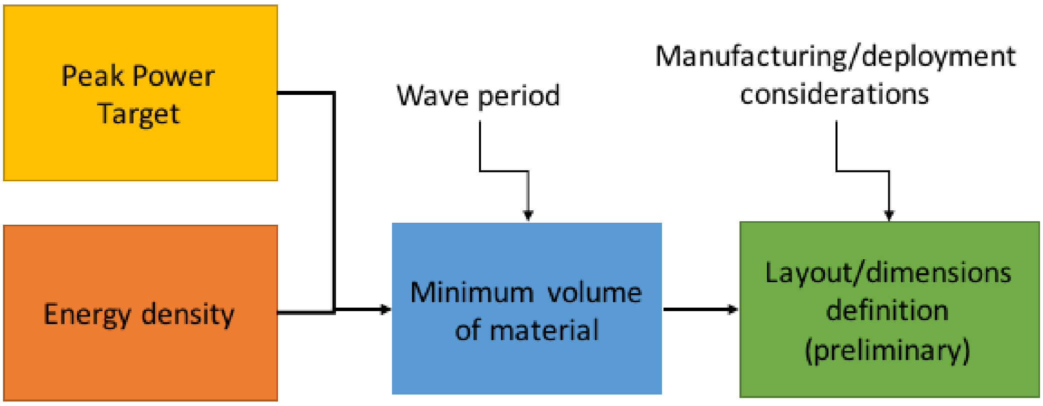


FIGURE 3.3-1: SCHEME OF THE APPROACH FOR THE PRELIMINARY LAYOUT AND DIMENSIONING OF THE DIELECTRIC ELASTOMER GENERATOR (DEG).

Concerning the Symphony concept, the geometrical arrangement of the DEG is particularly intricate since it has to be compliant with a yet complex architecture. However, given the peculiar dynamic capabilities of this WEC concept, it is foreseen that a particularly efficient dynamic matching could be found. Different solutions for the integration of DEG into the Symphony architecture are presented in Figure 3.3 1.

In the solution of Figure 3.3 1(a), the polymeric PTO is made of a DE layer (or stack of layers) coated between compliant electrodes. The DE membranes form a hollow shell, which has one face in direct contact with the trapped water volume, and the other face in contact with the air in the spring tank. The device operates between two configurations: when the outer cylindrical body of the WEC is maximally lifted, the DE membrane has nearly-cylindrical shape and its capacitance is minimum (Figure 3.3 1(a) left). As the outer cylinder goes down, water pushes the membrane and makes it expand in the transversal direction, up to a maximally stretched configuration (Figure 3.3 1(a) right) in which the capacitance is maximum.

A similar concept is sketched in Figure 3.3 1(b). In this implementation, the DE layers form an inflating nearly-spherical shell, the surface (and capacitance) of which is minimum when the Symphony outer cylinder is lifted (Figure 3.3 (b) left), and maximum when the outer cylinder is down (Figure 3.3 1(b) right). Due to kinematic constraints, it has been assessed that in both the configurations of Figure 3.3 1(a) and Figure 3.3 1(b) the water volume subtended by the DE shell has to vary between 0.4 m3 and 1.4 m3. In general, the architecture of Figure 3.3 1(b) is more promising, as it exploits isotropic spatial deformations of the DE membrane, which correspond to larger capacitance variations.

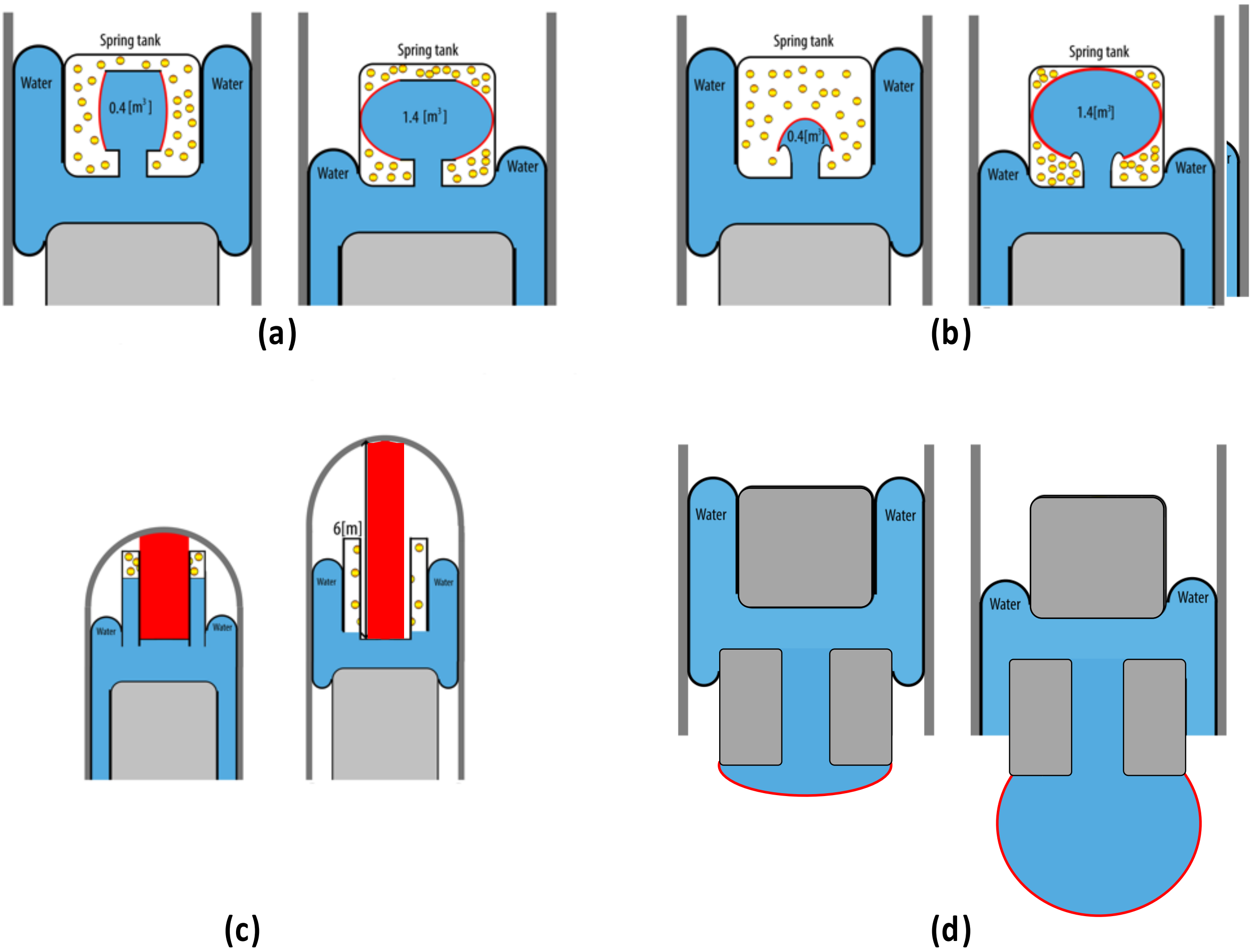


FIGURE 3.3-2: SCHEME OF THE WORKING PRINCIPLES OF FOUR DIFFERENT INTEGRATION STRATEGIES FOR THE DEG INTO THE SYMPHONY CONCEPT.

A different layout is represented in Figure 3.3 (c), where the DE PTO is constituted by a stack of planar membranes. The longitudinal axis of the device is parallel to the membrane faces (which house the electrodes). One of the DEG's edges is fixed to the WEC cylindrical outer body and the opposite edge contacts the water through a rigid sliding plate. As the outer cylinder raises, the DEG is pulled and expands in surface, up to a maximum capacitance configuration (Figure 3.3 (c) right). This concept appears to be of difficult implementation, and exploits uniaxial membrane stretch, which induces lower capacitance variations than biaxial bubble-like deformation.

Finally, Figure 3.3 (d) shows a layout in which the DEG is located at the bottom of the trapped water volume and it undergoes bubble-like expansion as the WEC outer body moves downward. This concept is interesting as it exploits biaxial membrane deformations, and, being based on larger diameter membranes, allows to reduce the overall thickness of the DEG (and the consequent number of layers). However, implementation of this solution would

require a substantial redesign of the lower assembly (compensation tank and cocoon) of the WEC.

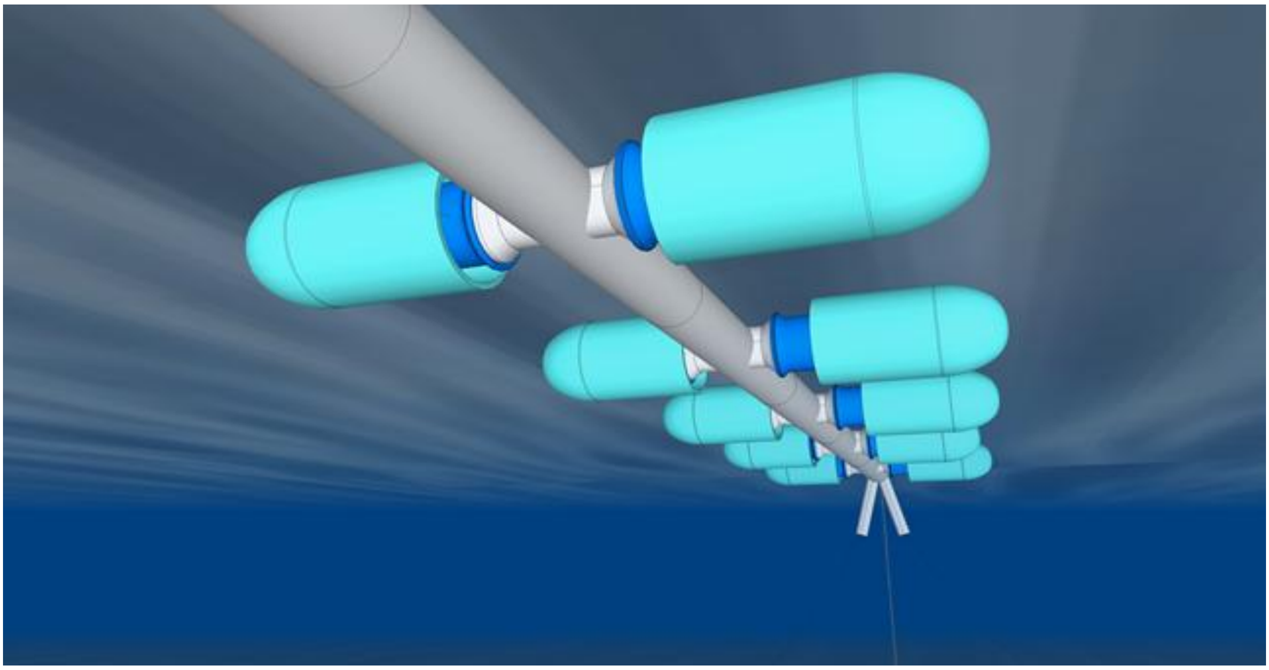
In the following, a preliminary estimate of the DEGs dimensions required to reach a target peak power with the envisaged architectures is presented. The followed approach is that described in Figure 3.3 . For each of the presented DEG layouts, a value of the cyclic convertible energy density has been estimated, based on previous experiments and theoretical operational constraints (break-down, rupture, etc.). On the basis of this prediction, and assuming an average wave period of 10s, approximate DEG dimensions have been found which guarantee a peak power of about 40kW.

Results are presented in Table 3.3 1. In the table, ed stands for the DEG convertible energy density per cycle per unit volume of material, and it is maximum for architectures (b) and (d), which exploit equi-biaxial deformation, and minimum for architecture (c), which undergoes purely uniaxial stretch. The elastomer density is assumed equal to 1000kg/m3. D and H are a diameter and a height respectively (and they represent characteristic dimensions of the considered DEGs), and s is the DEG thickness in a reference configuration. Ppk is the resulting power, assuming the parameters in the table, and, in all of the cases, it is approximately equal to the target of 40 kW.

These preliminary results can be used to identify the most promising architectures, on the basis of manufacturing considerations. A significant parameter for comparison is the DEG thickness, which is required to be as small as possible. Indeed, thick DEGs require a very large number of membranes to be stacked and assembled, thus requiring a very complex and costly manufacturing process. Architectures (a) and (d) appear to be the most promising ones, as (b) and (c) require excessively thick DEGs.

3.4. Preliminary considerations for shared moorings (compact aggregates)

The concept of "compact aggregates" as part of the breakthrough features in the WETFEET project is a rather generic approach to analyse the possibility of enhancing economic viability of WEC arrays by making use of their proximity to each other, in particular by rigidly connecting nearby devices between each other or to a common structure moored to the seabed. At conceptual level, this study is done in WP6 without being explicitly connected to a certain device type. For the particular case of the Symphony however, this feature could become a very important part of future developments, possibly being pursued already in the next phases. The Symphony concept at its present stage, like other linear heaving point absorbers, has an intrinsic issue with end stop forces and fatigue loadings that need to be countered by the mooring for every floater. It could become significantly more efficient to create a self-reacting system, where two horizontal floaters react against each other and moorings are only needed for station keeping. Such a design would be a typical example for



compact aggregates.

FIGURE 3.4-1: ARTIST'S IMPRESSION OF A COMPACT AGGREGATE FOR SYMPHONY. THIS IS A VERY INITIAL VISION OF A HORIZONTAL AND JOINT ARRANGEMENT. MOORING CONNECTIONS, AS WELL AS POSITION IN THE WATER COLUMN HAVE NOT BEEN VERIFIED. THESE ASPECTS WILL BE THE FOCUS OF A FIRST CONCEPTUAL DESIGN ROUND OF THIS TYPE OF ARRANGEMENT, IN A LATER PHASE OF DEVICE DEVELOPMENT.

3.5. Preliminary considerations for electro- mechanic PTO

At time of project planning, the decision for which type of PTO to be developed in prototype scale for the first Symphony trials had not been concluded. In particular two different PTOs

based on components widely used in other industry branches were considered: the linear spindle drive and the water turbine.

A) Linear spindle drive

The most straightforward vision of a PTO for a linear heaving WEC like the Symphony is an electro-mechanical linear drive, which is why in for the original Archimedes Wave Swing pilot plant a linear generator was selected. This option was equally considered for other devices (Wedge, OPT). The main reasons why the linear generator has not been chosen for the next development steps are: (i) its sensitivity to eccentric forces and very high bearing forces; (ii) the quantity of expensive and heavy permanent magnets and its inherent up-scaling limitations; (iii) its limited efficiency due to requiring high speeds for optimum operation. An obvious candidate for succeeding the linear generator is a linear spindle drive, the type of which is frequently used in industrial machines and has a very high degree of reliability and stage of development.

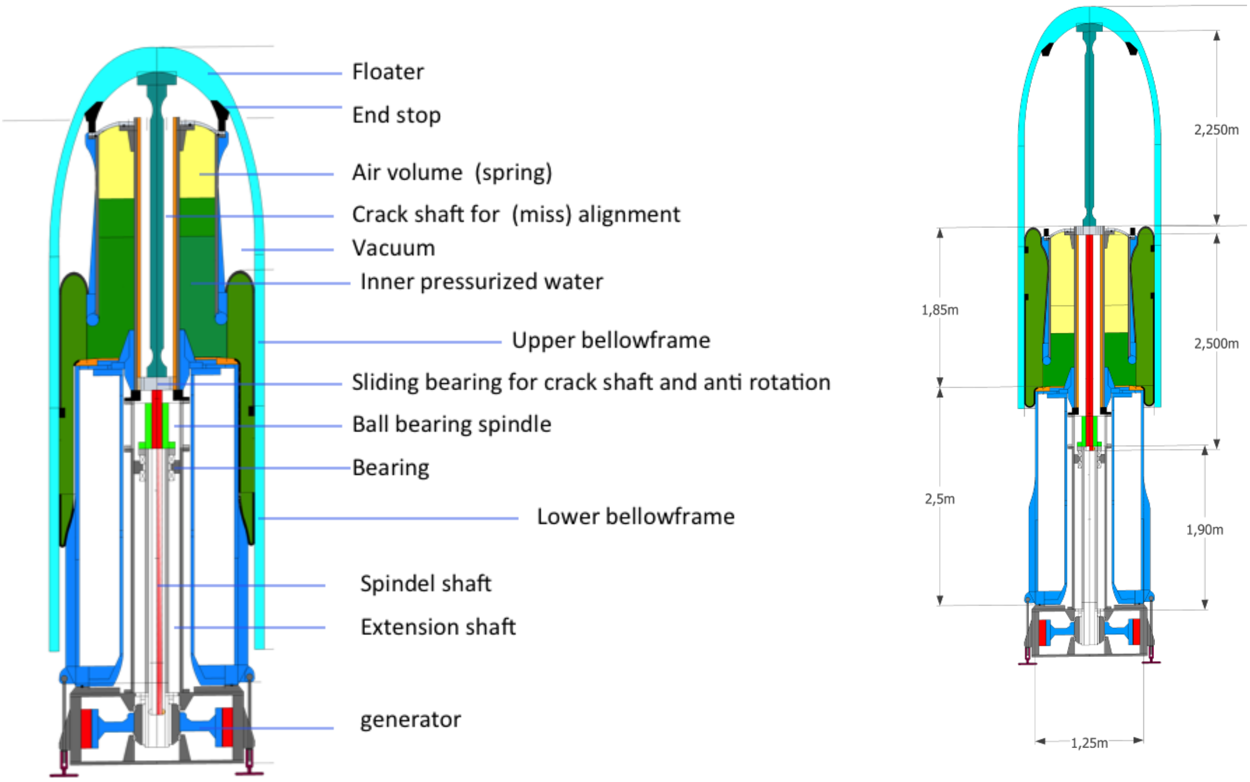


Figure 3.5-1: Initial conceptual design for integrating a linear spindle drive into the Symphony 1.5m diameter prototype.

However, the spindle drive dimensions and performance parameters required for integration into a Symphony prototype, as well as some uncertainty about its handling of the potential lateral eccentric loads and other operational needs of the spindle, made it the second choice at this stage, which is why it is not further discussed in the context of this report.

B) Water turbine

Due to the rather unusual operational environment of reciprocal flow (reversing every 5 seconds approx.) in varying high-pressure environment (15-20 bars abs. with varying gradients), a careful choice of the turbine type is an important first step. A comprehensive study of existing turbine types and their potential pros and cons for this case was conducted [de Jong,2015] , and an evaluation matrix elaborated. The below described turbine types were analysed taking into consideration the following weighted selection criteria: (i) Efficiency, (ii) Bidirectional, (iii) Pump functionality, (iv) Manufacturing, (v) Maintenance, and (vi) Reliability.

Concept 1: Pump as turbine

This concept uses a reversed conventional pump design to generate power. The pumps suitable for this purpose are rotary positive displacement pumps. The biggest advantage of this concept is that the pump design gives an excellent controllability of the system because the exact volume flow per rotation is known. Also positive displacement less sensitive to variations in pressure across the device. The selection of a specific type of pump is not relevant for now, but will be discussed if this concept proves to be the most suitable for either the prototype or the full-size model.

Concept 2: Impulse turbine

In an impulse turbine, water pushes against a turbine blade, deflects and loses velocity (kinetic energy) during the process. In conventional turbine applications, this often results in half-moon shaped buckets turbine blades. For the Pelton Wheel, the tangential inlet velocity of the water is twice the rotational velocity of the runner. An advantage of the impulse turbine is its simple construction. Impulse turbines are usually used for situations where the pressure drop over the turbine is large. However, they need to be air-filled as they are driven by jets of water (eg. Pelton Wheel, Curtiss Turbine, Turgo Wheel, Banki Turbine). It would be very difficult to keep such a component air filled in a submerged WEC.

Concept 3: Francis turbine

A reaction turbine accelerates the flow through the runner which exerts a force on the blades. Inlet guide vanes accelerate and swirl the fluid into a spiral casing. The flow enters the runner radially and leaves the runner axially. The axial velocity is constant over the runner, but the tangential velocity is decreased to (almost) zero. The reduction in rotational velocity is a consequence of the energy extracted from the flow. Radial turbines are able to extract energy very efficiently with small pressure drops and significant fluid flows. A large disadvantage, if not exclusion criterion, of a radial turbine is that it is not reversible. A complex arrangement with extra tubing and valves is necessary to use this concept as a bidirectional turbine or as a pump.

Concept 4: Kaplan turbine

The axial turbine concept is based on advanced developments of the radial turbine. The axial turbine also decelerates the fluid flow in the tangential direction, but the direction of the flow is not changed over the runner. The axial turbine is able to extract energy efficiently over a wider range of operational conditions than the radial turbine. By using adjustable blades, the turbine does not have to change rotation direction if the flow is reversed. Also the blades can be positioned in an angle so the turbine operates as a pump. However, adjustable blades are complicated to operate, bring along additional maintenance concerns and are costly in an early phase of
production.

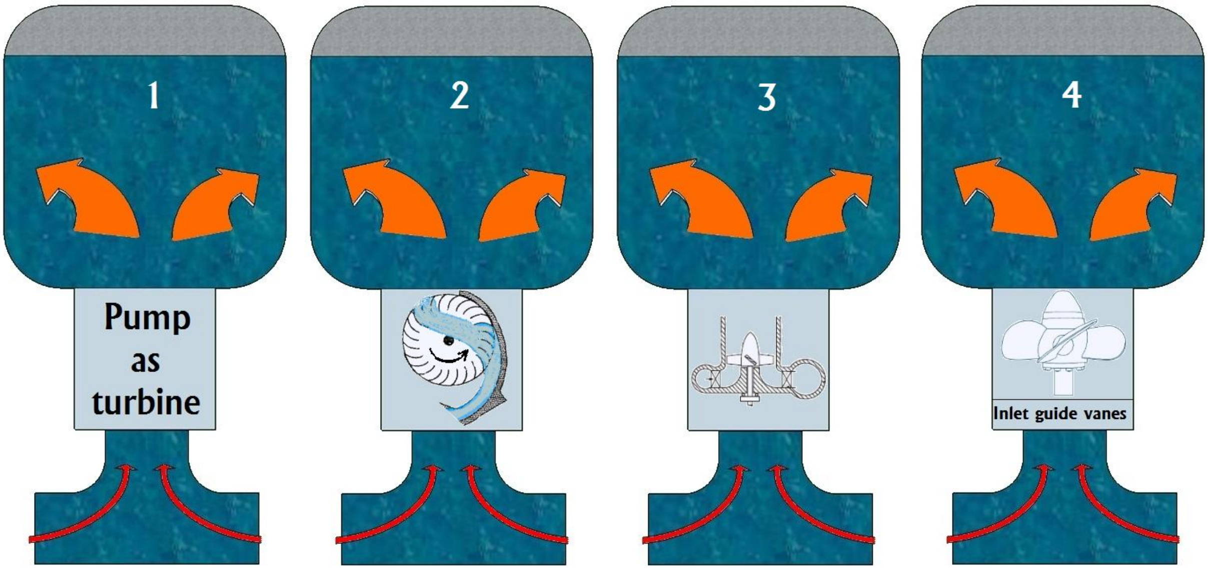


FIGURE 3.5-2: TURBINE CONCEPTS 1: PUMP AS TURBINE, 2: IMPULSE, 3: FRANCIS, 4: KAPLAN [DE JONG,2015].

As a result of this concept evaluation about existing turbine types and their suitability for the Symphony application, it was concluded that a positive displacement pump (e.g. a lobe pump) is best suited for physical implementation into the 1.5m prototype, and equally promising for later stages of development (for which the axial turbine also showed promising potential).

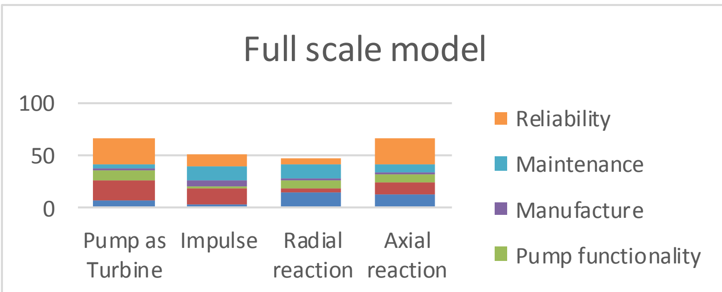


FIGURE 3.5-3: RESULT OF THE CONCEPT EVALUATION STUDY FOR SUITABILITY OF TURBINE TYPES FOR SYMPHONY INTEGRATION AT FULL-SCALE: BOTH POSITIVE DISPLACEMENT PUMP AND AXIAL TURBINE SHOW MORE THAN 65 OUT OF 90 POINTS (WHEREAS FOR THE 1.5M PROTOTYPE, THE POSITIVE DISPLACEMENT PUMP CLEARLYSHOWED THE BEST POTENTIAL [DE JONG,2015].

After concluding that the positive displacement pump as turbine is the best option for the Symphony operational case, the conceptual design and power rating calculations are under way as preliminary work for WP4. It is intended to over-dimension the power rating of the PTO unit for the 1.5m prototype, in order to allow for controllability of the total system motion in all situations, and even to enhance the ability to move the floater against the pressure of the internal spring if needed. Whereas for full-scale devices such an option would be unrealistic, the cost-benefit ratio in an early development stage justifies this choice.

With respect to the exact type of pump, there has also been a comprehensive review of the following existing rotating displacement pump technologies: (i) Lobe pump, (ii) External Circumferential piston pump (ECP), (iii) Gear pump, (iv) Screw pump, (v) Variable vane pump, (vi) Flexible impeller pump and (vi) Peristaltic pump (not reversible).

The pumping motion in the gear pump is arranged by two gears. These gears do not require an external synchronisation system, which simplifies the design. However, the gears are only self-lubricating when highly viscous fluids are pumped, like oils. For the Symphony, water will be the working medium through the pump. The continuous changing direction of rotation in combination with unlubricated gears will be very harmful for the gears. This is unacceptable for a design where durability and reliability are of high importance. The flexible impeller pump and peristaltic pump are only used for small flow rates up to 10 litres per second [Volk,2000] . The runner of the variable vane pump is in constant contact with the surface of the pumping house. This increases the wear rate of the vanes. Another disadvantage is that the moving vanes require a complex rotor design and increase the number of moving parts. The disadvantage of screw pumps is that the design and manufacturing of a rotor is a complex and expensive process where there are no clear advantages to start designing such a rotor.

The design of the pumps described above does have issues with wear, simplicity or costs. The lobe and ECP pump remain simple in design and are able to work under the given operational conditions. Both design require an external synchronization system. This makes the design a little more complex, but also gives the opportunity to lubricate the gears.

For the final choice on which runner type to choose for the pump-turbine, an analysis of existing operation environments of lobe pumps and ECP (see Figure 3.5 4), as well as a more detailed analysis of operational characteristics and ease of design, manufacture and maintenance was carried out.

FIGURE 3.5-4: LEFT: TRI-LOBE, RIGHT: ECP DESIGN [FRISTAM PUMPEN]

The standard lobe pump with three lobes is usually used for handling food products containing fragile solids. The ECP design (and the very similar bi-wing design) is used for low viscosity fluids and has a longer and tortuous path between the runner and casing which reduces slip and thus increases the volumetric efficiency of the pump. The ECP design seals in the centre between the lobe and the rotor of the counterpart, and it has been reported as durable and reliable. Technically, the ECP is the most suitable design for the Symphony, due to the reduced slip. However, initial dimensioning exercises have been made using the classic lobe pump design, due to experience from earlier projects and a more straightforward trial-and-error process with this model. For the turbine design and manufacture in WP4, it is envisaged to develop a special ECP pump design, as well as build and bench-test a prototype.

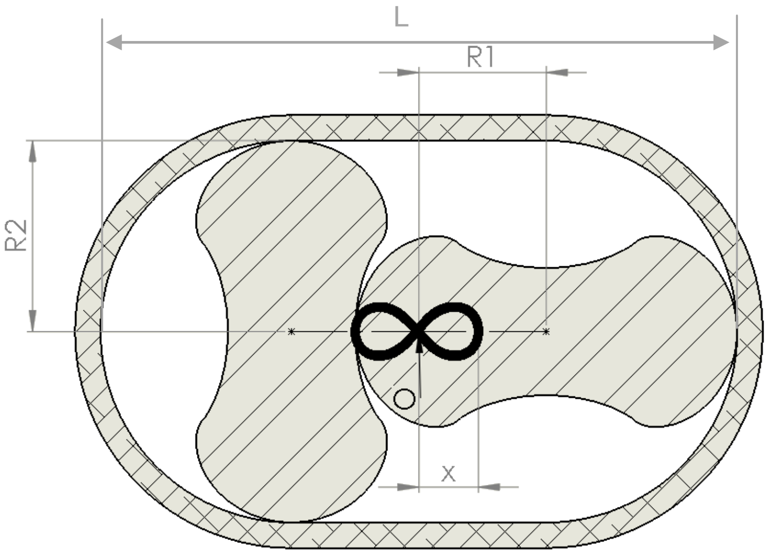


FIGURE 3.5-5: LOBE PUMP GENERIC FUNCTION SKETCH

For the given input variables, the required axial length Z can be calculated for a range of L: Q.req =0.13 m^3/s; Rotational speed [revolutions per minute] N =300 rpm.

Length L	R.2	R.1	D	Q	Z
m	m	m	m³/r	m³/s	m
0.35	0.102	0.073	0.0296	0.148	0.88
0.4	0.117	0.083	0.0387	0.193	0.67
0.45	**0.131**	**0.094**	**0.0489**	**0.245**	**0.53**
0.5	0.146	0.104	0.0604	0.302	0.43
0.55	0.161	0.114	0.0731	0.365	0.36
0.6	0.175	0.125	0.0870	0.435	0.30

Based on these simplified calculations, the approximate dimensions for the turbine have been derived. These are not expected to change significantly by using another runner type, which is why an estimated axial length of 50cm and duct diameter of approx. 50cm is required for the 1.5m diameter prototype.

In WP-4, detailed calculations for the chosen runner geometry, as well as flow simulations including inlet and outlet geometry will be conducted for the ECP runner type for both 1.5m prototype and the reference 6m Symphony model, before the final design is subject to more complex analysis preceding the prototype manufacture.

4. INSTALLATION AND MARINE OPERATIONS

The installation process, both the land-based assembly of major parts and the marine operations related to mobilasation and demobilasation operations, are designed with the principle of modularity and avoiding heavy equipment. Especially for the marine operations of a 6m device, a simple tug boat and a support launch vessel are expected to be sufficient. Maintenance (either disconnecting the entire device or thecocoon removal) will be done by divers, and potentially simple ROVs with one grabber, and common diving auxiliary equipment (parachutes). A main constraint is the legally established weather window for professional diving, which is in the range of sea states of safe handling of the WEC.

In the following, the complete assembly and sea installation is outlined.

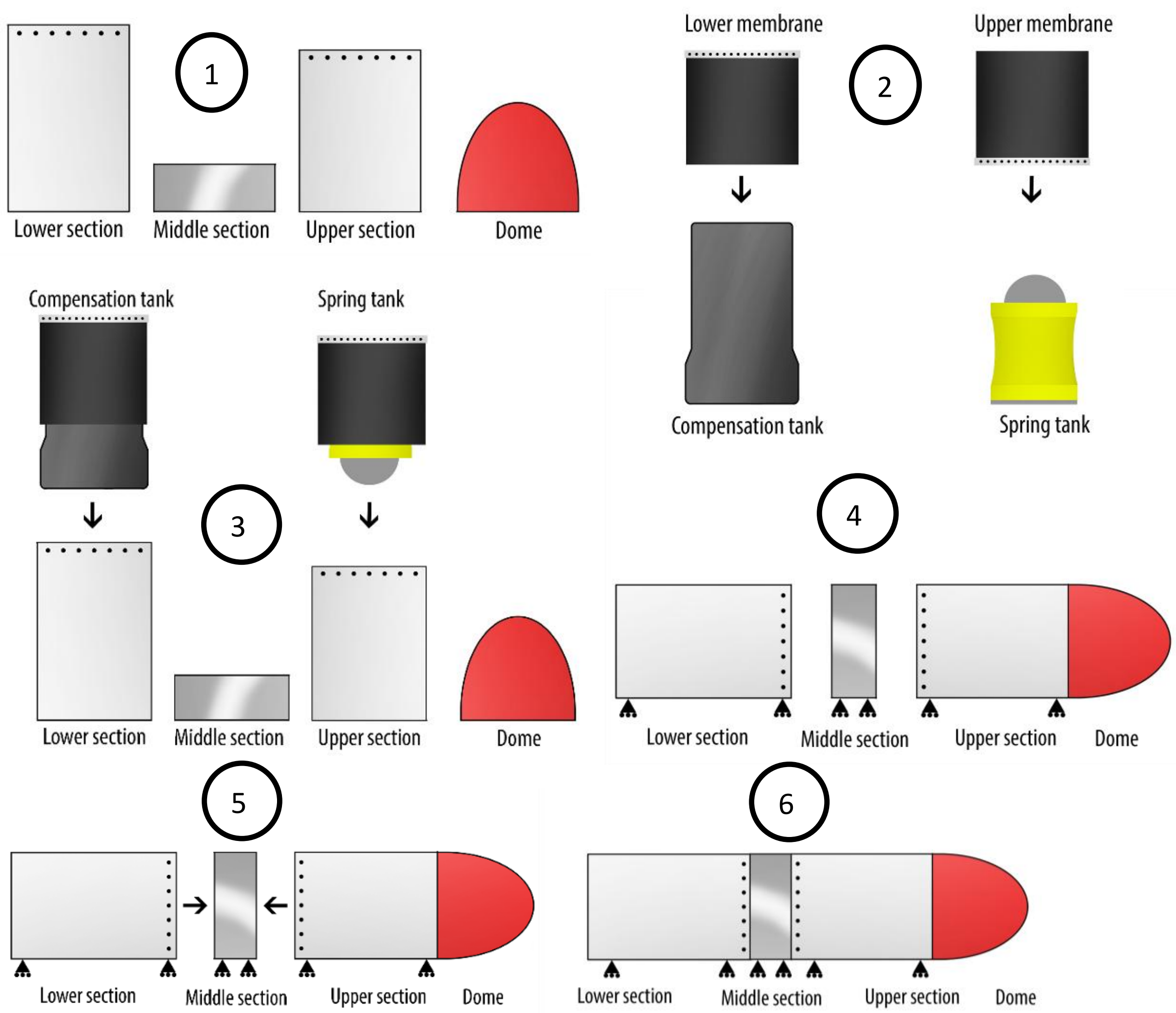


FIGURE 4-1: ASSEMBLY OF SYMPHONY DEVICE - OUTLINE: 1-HULL PARTS OF THE SYMPHONY ARE PLACED VERTICALLY; 2-THE MEMBRANES ARE CONNECTED TO THE INNER TANKS USING A CRANE; 3-TANKS WITH

membranes are placed in the hull of the Symphony from the top using a crane; 4-The hull parts are placed horizontally; 5-The hull parts are pushed against each other; 6-The parts of the hull are connected together

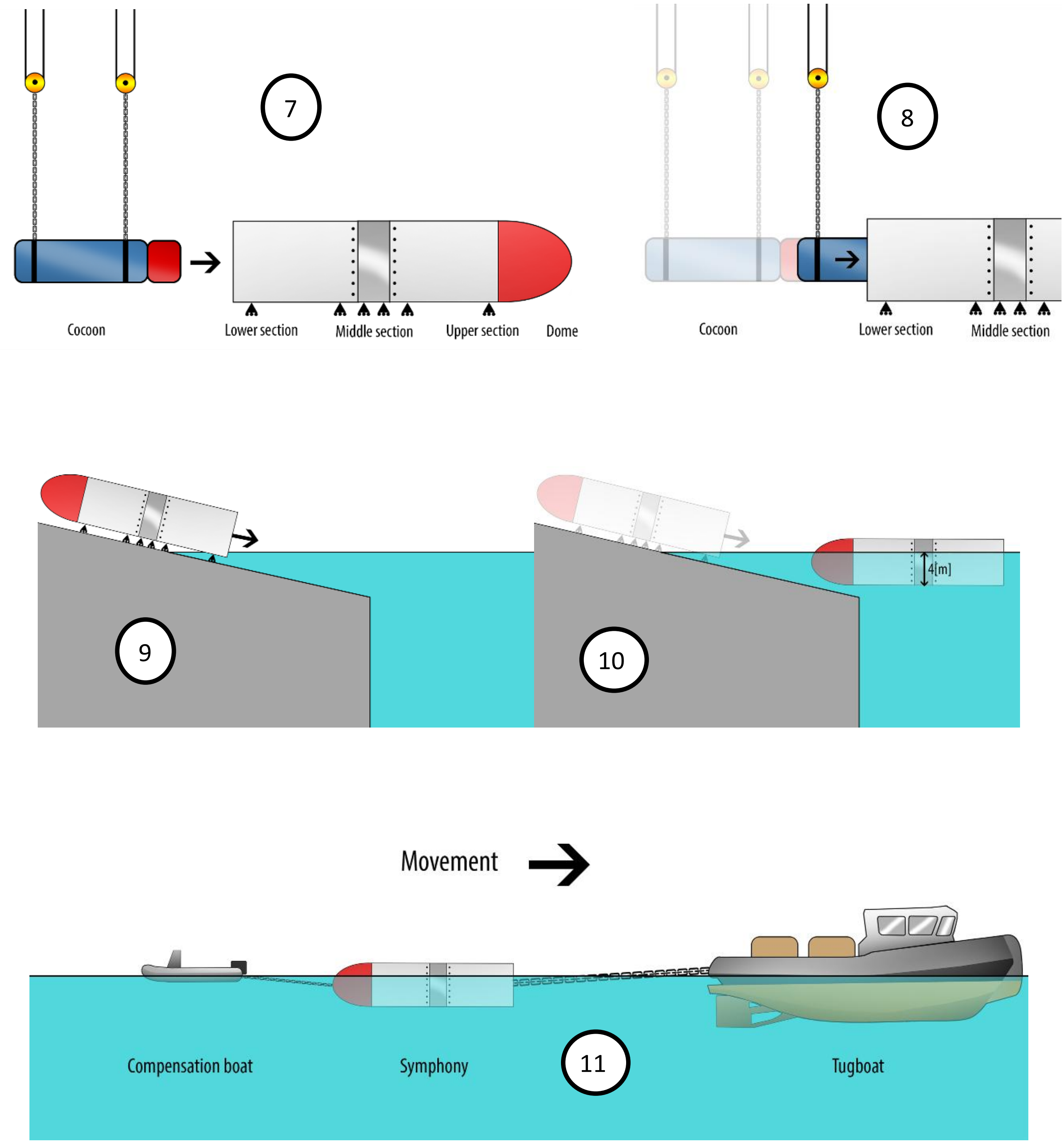


Figure 4-2: 7-The cocoon is mounted in a overhead crane using two connections; 8-The cocoon is placed inside the Symphony; 9-The Symphony rolls down a hill into the water; 10-The Symphony is placed in the water with a submergence depth of +/- 4m; 11-The Symphony is pulled through the water to the installation site using a tugboat. A small boat will pull in opposite connection in order to prevent the Symphony from colliding with the tugboat. The

CONNECTION BETWEEN TUGBOAT AND SYMPHONY COULD BE MADE BY A RIGID ROD, SAVING THE SMALL BOAT.

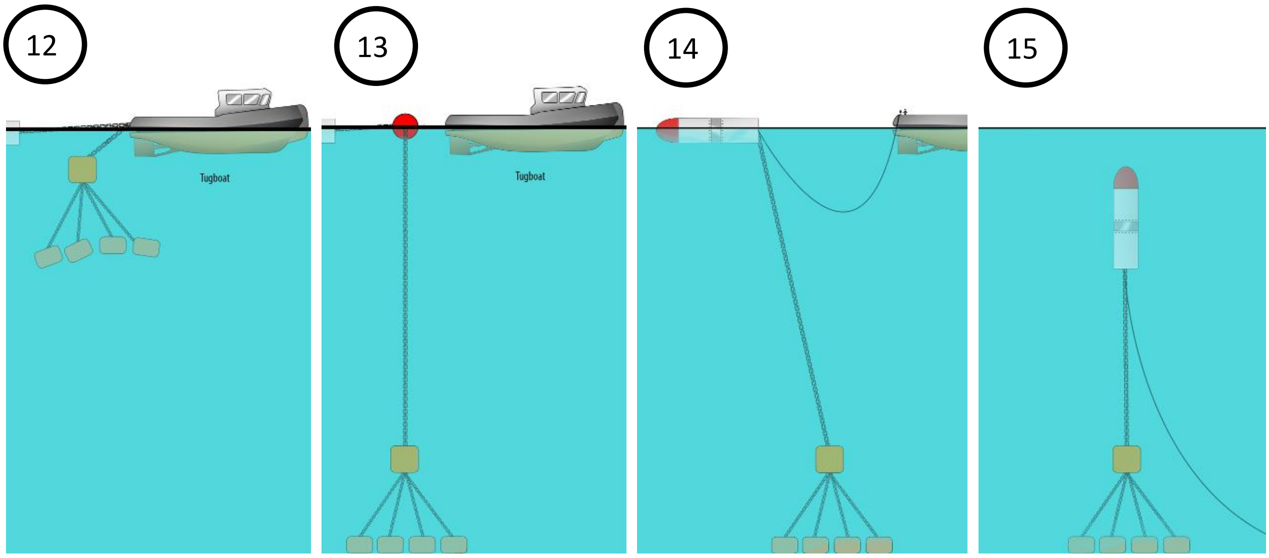


FIGURE 4-3: 12- THE TUGBOAT RELEASES THE ANCHORING SYSTEM INTO THE OCEAN; 13-ANCHORING SYSTEM IS AT THE BOTTOM OF THE OCEAN, A FLOATER BUOY IS PLACED AT THE END OF THE ROPE IN ORDER TO LOCATE THE ANCHORING SYSTEM; 14-THE SYMPHONY IS CONNECTED TO THE ANCHORING SYSTEM, THE FLOATER BUOY IS REMOVED AND THE SYMPHONY IS LOWERED BY CONTROLLING THE WINCH IN THE SYMPHONY; 15-SYMPHONY IS INSTALLED AND THE CONTROL/ELECTRICITY LINE IS CONNECTED TO THE SHORE.

The Symphony is designed for allowing the device structure to remain in position and remove only the control cocoon with all vital components and controls (see 3.2). However in case of necessary demob operation of the entire device, or for decommissioning, the installation process can be reversed in a relatively straightforward manner, with equivalent marine equipment.

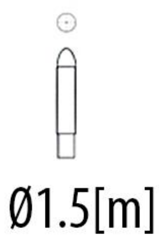
Minor maintenance and inspection activities are planned to be conducted by divers, at least for the initial phase of development (e.g. demonstration farm with several 6m devices). Despite widely considered costly and potentially involving higher risk manual labour, divers have shown to be a very efficient means for light operations in up to 20-30m depth in the Archimeds Wave Swing Pilot trials in 2004. For deeper depths and looking more into the future, ROV and AUV technology, including mechanical grabbers and other auxiliary equipment, is undergoing a fast development, which in 5 years time will allow re-designing the inspection and maintenance strategy.

5. PRELIMINARY DESIGN (INCLUDING DIMENSIONS)

5.1. Design specifications

In order to have comparable cases in the preliminary design and breakthrough integration processes for the Spar OWC (Deliverable 2.1) and the Symphony, three reference diameters were chosen for each device type. The smallest diameter (scaled prototype, d=1.5m) was chosen to allow for WETFEET component development at a reasonable cost, ensuring, at the same time, a meaningful dimension for e.g. initial sea trials. The first series for niche applications is likely to have a diameter in the range of 6 m, and a utility-scale device 12 m

	1.5m	6m	12m
Stroke [m]	2.0	8.0	8.0
Hull height [m]	7.0	25.0	30.0
Mass [t]	10	650	3200



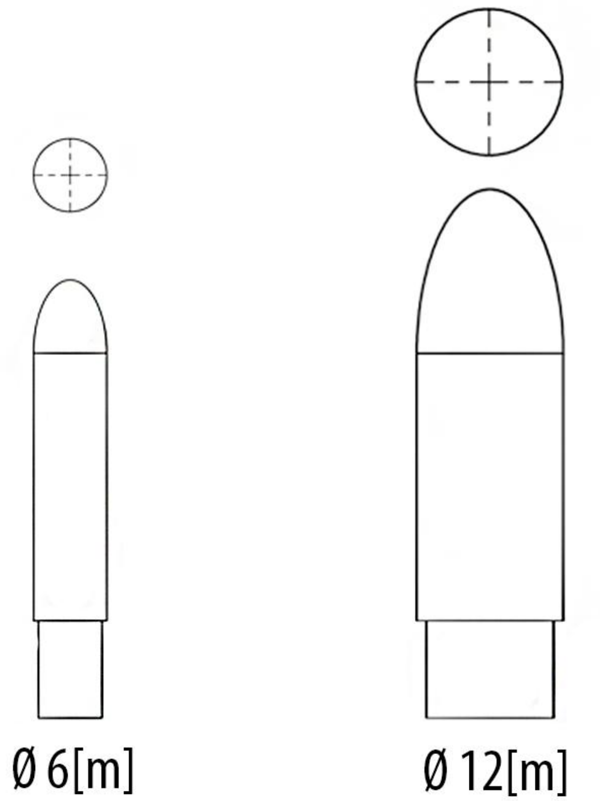


FIGURE 5.1-1: DEVICE DIMENSIONS CHOSEN FOR ANALYSIS WITHIN WETFEET: 1.5M DIAMETER FOR PROTOTYPE COMPONENT DEVELOPMENT AND INITIAL SEA TRIALS, 6M FOR NICHE APPLICATIONS AND 12M FOR UTILITY-SCALE APPLICATIONS.

Whereas the focus of some WETFEET tasks is on the development, manufacture and physical testing of components (membrane, turbine), the general scope of WP-2 is to anticipate a realistic vision for global device layout and the verification of whether the components to be developed fit into the structure as initially envisioned.

The main purpose of the preliminary design process presented in this report is to anticipate the most critical aspects for future full-scale devices, as well as benchmark the components that will be developed as prototypes within WETFEET, in other WPs.

For Symphony, this comprises the following analyses:

Membrane dimension and shape: the membrane and its guide walls need to be specified at an early stage, as a physical prototype is due to be manufactured and tested in the scope of WP3. Another reason to focus on the membrane design in an early phase is the need for inputting parameters into the structural calculations for the hull, which is a critical device design parameter.

Preliminary structural analysis of hull: at this stage a realistic preliminary estimate of the required strength for the hull and other large structural elements is a priority, as this influences the material choice and has relevant impact on the costs. A more accurate analysis of the structural properties of the hull makes more sense once there is a decision on the overall device design and components.

Required dimensions and space available in the structure for the components: turbine, generator, air/water (spring) chamber, compensation tanks and cocoon (see Figure 2.1 1). This had been done with assumed smaller dimensions of the inner cylinder than at present stage of the design process, and thus became uncritical. Due to the required weight/buoyancy ratio and a detailed sum of structural weights for all the components, the preliminary design of the Symphony had to be revised resulting in a longer hull and inner cylinder, as presented in Figure 5.1 1. No further analysis is deemed relevant at this stage. The exact turbine and control cocoon dimensions will be determined within the available limits in WPs 3 and 4.

The most relevant load cases and consequential focus of the preliminary structural analysis for the Symphony device are therefore substantially different from the analysis of the Spar OWC, which is why the procedure presented in this report varies from the procedure followed in Deliverable 2.1.

Whereas for the hull strength estimate the most critical load cases are calculated with estimated (pessimistic) input values, a more accurate structural analysis would not be meaningful without a motion analysis. For this reason, a simplified motion analysis was prioritised at this stage of the project, in order to determine device's position and orientation in extreme load cases, so as to obtain pressure distributions on the hull (see section 5.3). Furthermore, this allows identifying possible critical situations that were not anticipated in the assumptions.

In the following, the main design tasks for the Symphony in the context of WETFEET, in particular the membrane shape and hull strength, are further approached.

A) Membrane

Being a key component of the Symphony concept, and bearing inmind the need of defining input variables for the manufacture of the structural membrane in WP 3, the dimensions of the structural membrane were a priority of the design process in an early phase. Due to its function as end of stroke (EOS) mechanism, the membrane, together with the guiding shape of the inner wall, is potentially the most important design detail for appropriate operational dynamics. On the one hand, it has to maintain a stable radial centering force versus the internal over-pressure. On the other hand, it must roll up and down along the inner guide walls and hull without major friction losses. The guide wall shape must be very accurately dimensioned, in order to allow for the desired functions of linearising the spring and functioning as inherent end stop without mechanical shock loads.

Material choice and operational condition range have been determined in a conceptual design phase by Teamwork and Trelleborg:

- Upper membrane external exposure Air (at a relative vacuum of 80%).
- Operational stroke h = 2m; full stroke (in end stop function) h = 4m.
- Operating pressure p=10-20 bar (o); alternating cycles n = 30 000 000 cycles.
- Lifetime t = 10 years; minimum span 75 mm; maximum span +/- 210[mm].

The minimum and maximum span, as well as the exact shape of the guide walls, has been calculated with the in-house time-domain model [Kooiman,2015]. The inside wall geometry acts as a negative spring that linearizes the air spring. The membrane must be able to work properly at different dimensions since the dimensions of the inside geometry might be changed due to the optimization of the spring. The membrane should still be able to operate if the upper wall geometry changes by 20%. Once the membrane reaches the inversed shape of the guide walls, its acceleration vector turns downwards, and braking is induced.

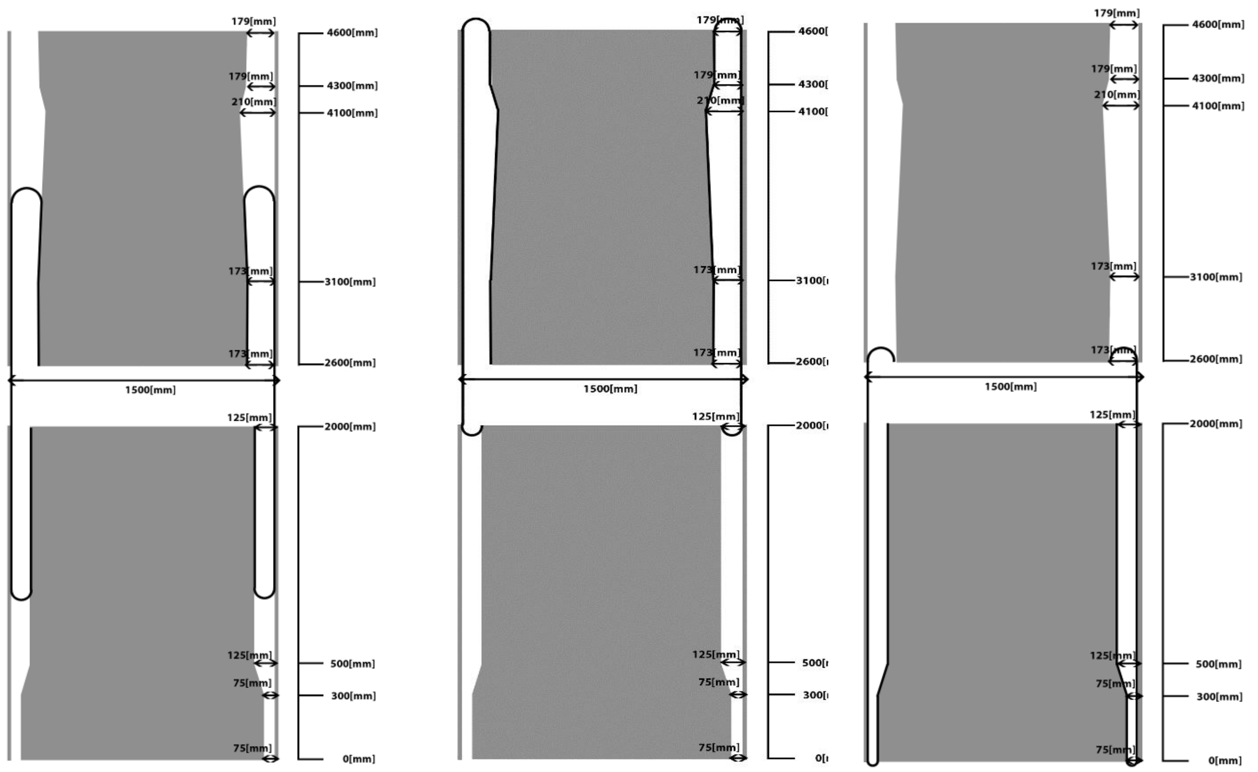


FIGURE 5.1-2: STRUCTURAL MEMBRANE AND GUIDE WALL DIMENSIONS FOR 1.5M DIAMETER PROTOTYPE. LEFT: UPPER FLOATER POSITION, CENTRE: FLOATER MID POSITION, RIGHT: LOWER FLOATER POSITION. DIMENSIONS EXEMPLARY AND PRELIMINARY, CALCULATED WITH TEAMWORK'S IN-HOUSE TIME-DOMAIN MODEL [KOOIMAN,2015]

B) Hull

The internal components of Symphony are expected to be relatively straightforward to scale up, as the internal operational environment between the 1.5m prototype and a full utility-scale 12m device would not substantially differ. The main distinction will be the structural hull, for which the 6m diameter is taken as a reference case. The outer cylinder of the Symphony protects its internal components from being exposed to the seawater. The outer cylinder itself is exposed to the ocean forces and corrosion by seawater. In order to design a sufficiently resistant outer cylinder, the load cases need to be known. In order to pick the right material, construction and thickness, a comprehensive material research has been carried out [van Noorloos, 2015]. A risk analysis was made for the outer cylinder in order to determine the possible damage points. The following risks were identified as major threats to the Symphony's structural integrity:

Corrosion

The outer cylinder is placed in ocean water, which is a corrosive environment. Over time the material of the outer cylinder may corrode and cause leakages or possible damage, unless it is made of non-corrodible material.

Exploding due to high pressure

While operational, the hull is exposed to a high alternating pressure. The high tension due to the high pressure could cause the hull to break.

Compression imploding (Buckling)

A part of the air inside the outer cylinder is taken out creating a partial vacuum. The SWP will be placed in underwater which results in a compressive force. The compressive forces could cause the outer cylinder to fail due to buckling.

Fatigue damage

Due to the many cycles of changing pressures caused by the waves, the outer cylinders' material could be destroyed due to fatigue stress

In the following, the assumed worst-case scenarios during operation and in survival case in extreme sea states are outlined.

5.2. Preliminary structural analysis

Scope and method

The aim of this exercise is to obtain a safe estimate for the required strength of the hull, as this can be an important cost factor for the overall device. Although it is not part of WETFEET to design a complete Symphony device with hull and other main structural elements, a realistic assessment of the material strength requirements for key parts of the device is vital for evaluating the overall device concept and practicalities regarding the integration of breakthrough components.

In the following, an extract of the structural finite element (FE) analysis of the hull of the Symphony WEC is presented. The overall goal of the analysis is to find the minimum material thickness of the hull required for a range of material types. This exercise was completed for the 1.5m diameter prototype in [van Noorloos, 2015] , and the most critical cases have been applied to the 6m reference device.

The model of the hull has been dimensioned in a 3D CAD model. The software used in order to make the finite element analysis is Solidworks Simulation 2010. Both metal/steel types and composites are included in the calculations. Initially, 5 material types had been included in the analysis, and for the calculation of the 6m Symphony models are focusing on plain carbon steel and E-glassfiber/epoxy composite. The Symphony is considered as a single piece part. The FE analysis excludes the flanges and other structural details of the device.

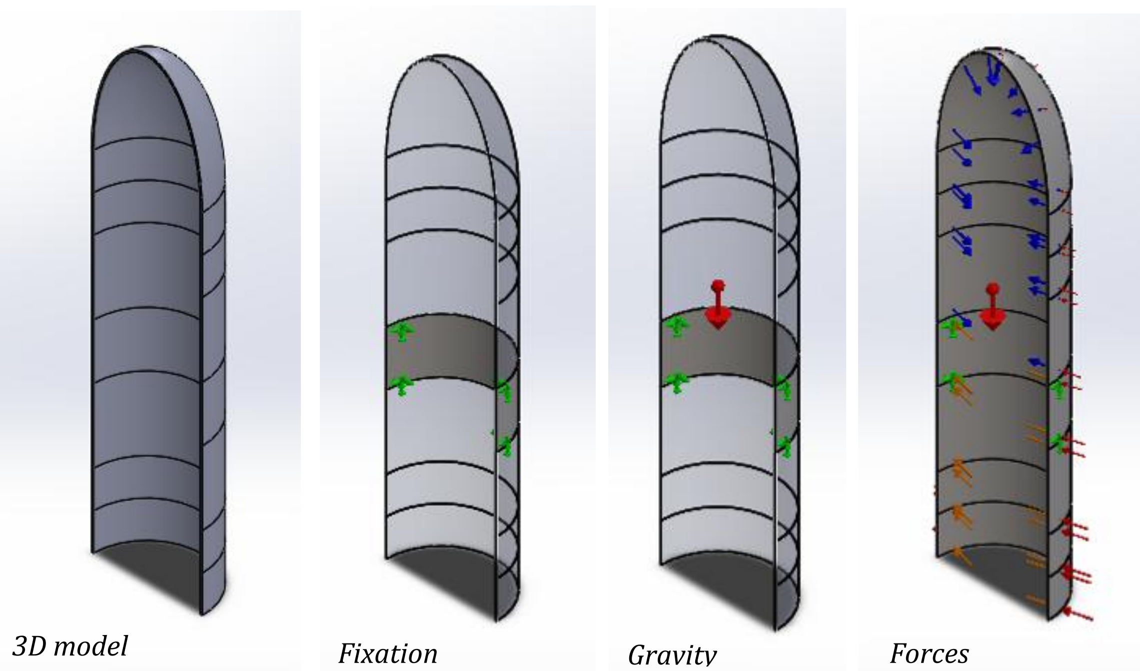


FIGURE 5.2-1: INPUT GEOMETRY AND LAYOUT OF FE MODEL FOR PRELIMINARY STRUCTURAL ANALYSIS OF HULL

Hydrostatic loads

The determination of the load by hydrostatic pressure, together with the results of the material research, is the basis for the finite element analysis for the outer cylinder. The results of this analysis provide the first indications for the design of the outer cylinder.

Dynamic influences like drag, wave radiation and cavitation are not included in the calculations, and assumed as negligible. The waves differ in height and period over time. The dynamic effects of the waves' motion are not considered in the load case. The hydrostatic pressure of the waves differs depending on the wave's height and position relative to the outer cylinder. The hydrostatic pressure caused by the wave is calculated using the following formula:

$$p_{hs} = -\rho g z, \qquad (5.2\text{-}1)$$

where p_{hs} is the hydrostatic pressure (Pa), ρ is the water density (kg/m^3), g is the acceleration of gravity (m/s^2), z is the height of the water column (m).

Internal vacuum

The dome of the SWP is subjected to a vacuum in order to make sure the air inside the dome does not influence the spring behaviour and/or push on the membrane due to air compression. At the present design stage there is no reliable estimate for how much vacuum is needed and feasible. For this reason a 100% vacuum will be considered in the force calculations. The vacuum generates a force that compresses the outer cylinder.

The closer a vacuum reaches the 100% relative vacuum, the more it can contribute to leakage and buckling (and, in extreme cases potentialy diffusion processes), which is why the assumption of 100% vacuum is on the safe side.

Internal over-pressure

The membrane is filled with water. As the outer cylinder (hull) moves down, the water moves inside the spring chamber, compressing the air inside the spring chamber. If the outer cylinder is at its top position the pressure inside the membrane will be 1 MPa If the outer cylinder is at its lowest position the pressure inside the membrane will be 2 MPa. The membrane rolls over the outer cylinder's surface, so that the membrane contact surface moves. Adding the forces to the instantaneous pressure differential between water column and vacuum on the other side of the membrane generates a potentially critical specific load case, in particular with respect to fatigue.

The most relevant load cases for the design of the major structural elements of the Symphony are therefore the maximum (static) submersion in extreme seas (survival load case) and the maximum operational load case, for which most likely fatigue becomes the most critical aspect.

Survival load case

In extreme sea conditions, the Symphony will be pulled down using the mooring system, for system survivability reasons When the system is pulled down with high waves, the compressive force of the water is at its highest. This is expected to correspond to a level of hull submergence of 20m from the mean water level. It is further assumed that in the worst case scenario the wave pushes the device sideways at an angle of 45 degrees (see section 5.3 for further considerations). The maximum wave height of 28.6m is used for this load case, resulting in a total submergence of 48.5m.

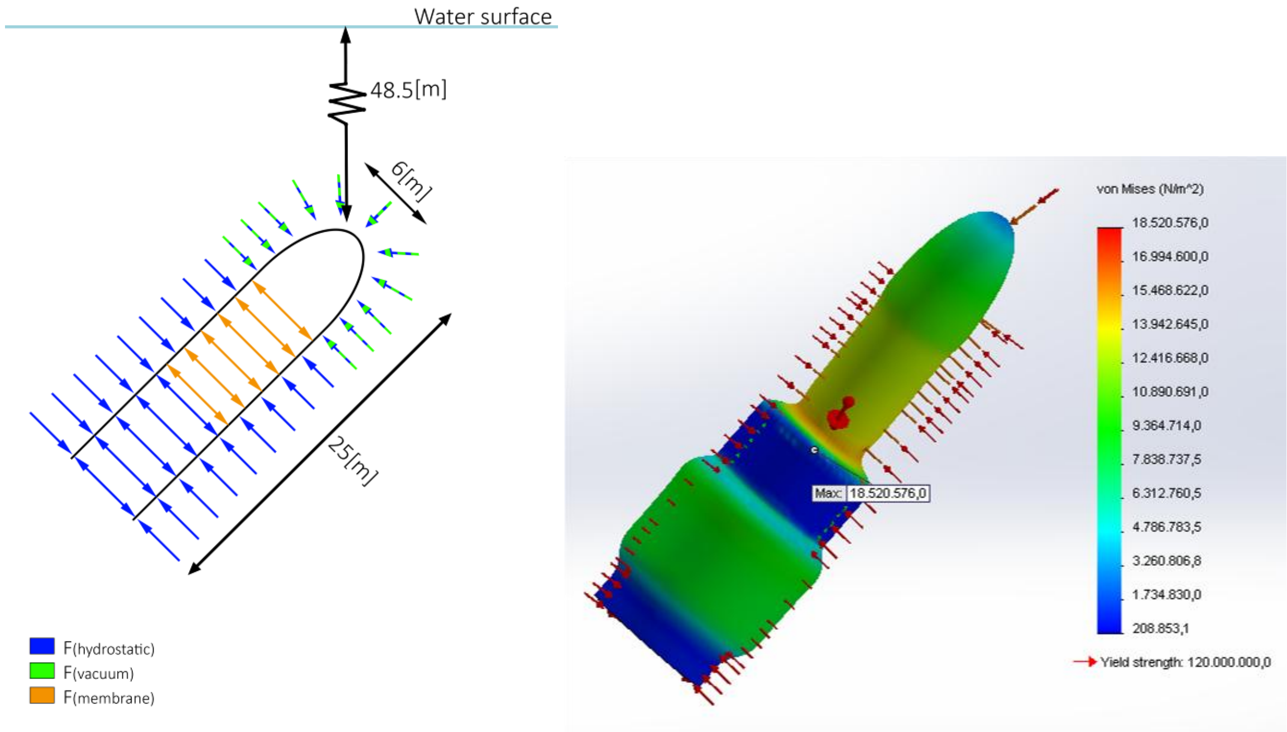
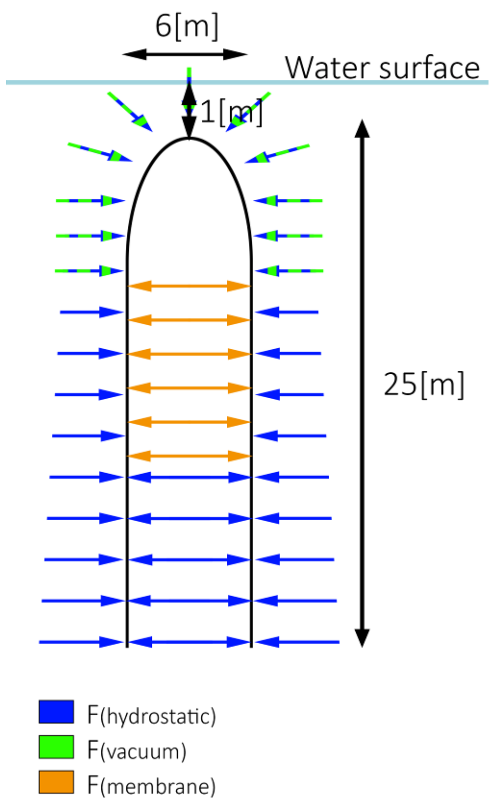


FIGURE 5.2-2: LOAD CASE DEFINITION (LEFT) AND RESULTS (RIGHT) OF INITIAL FINITE ELEMENT MODEL FOR 120mm GLASS FIBRE EPOXY AS HULL MATERIAL. MAXIMUM VON MISES STRESSES OF 18.5 MN/m^2 OCCUR IN THE LOWER ZONE OF THE CYLINDRICAL PART, ADJACENT TO THE MEMBRANE CONNECTION (YIELD STRENGTH=120MN/mm^2).

The outer cylinder has a linear, non-uniform pressure distribution since there is a height difference between the lower and the upper part. The hydrostatic pressure is an overpressure, not an absolute pressure compressing the outer cylinder. The compressive powers subtracted from the total formula.

Maximum operational case

It is assumed that a maximum operation conditions, the hull will be exposed to the maximum wave height of 10m, while the hull is submerged 6m below the ocean surface.



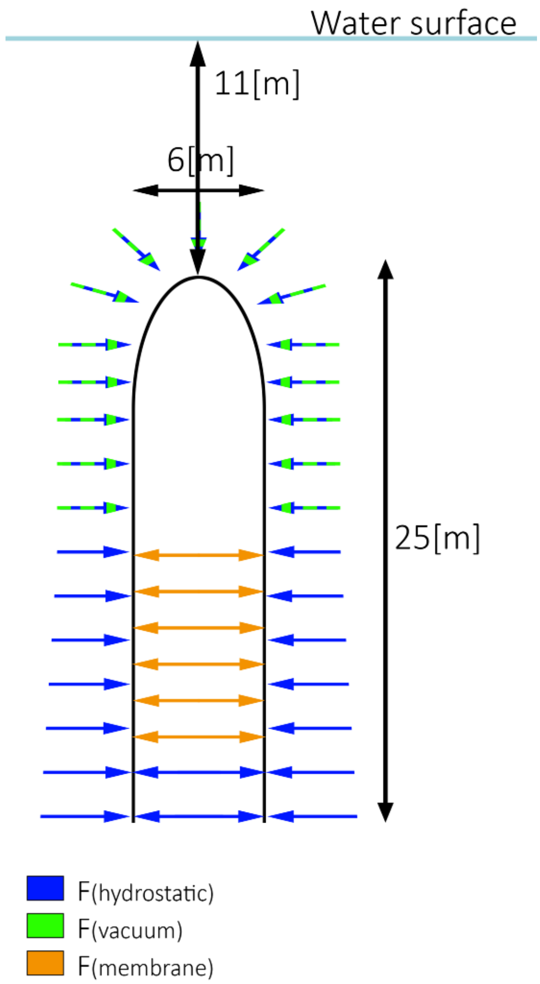


FIGURE 5.2-3: LOAD CASE DEFINITION (ABOVE) AND RESULTS (RIGHT) OF FE MODEL RESULTS OF 120mm GLASSFIBRE EPOXY

The most relevant load cases for the design of the major structural elements of Symphony are therefore the maximum (static) submersion in extreme seas (survival load case) and the maximum operational load case, including fatigue.

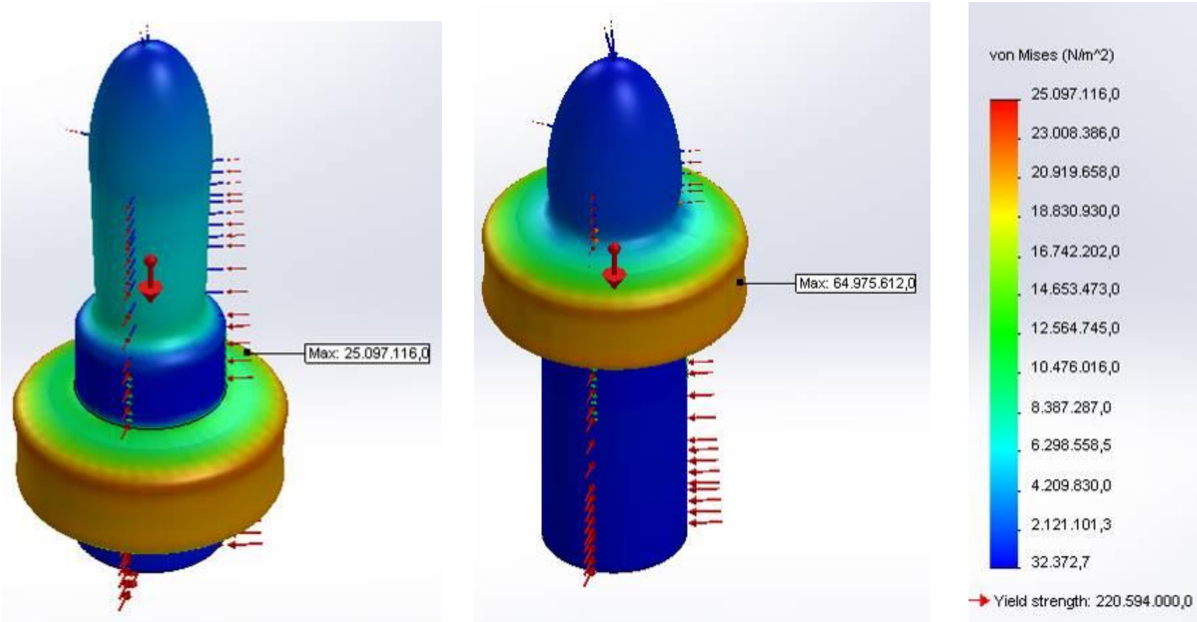
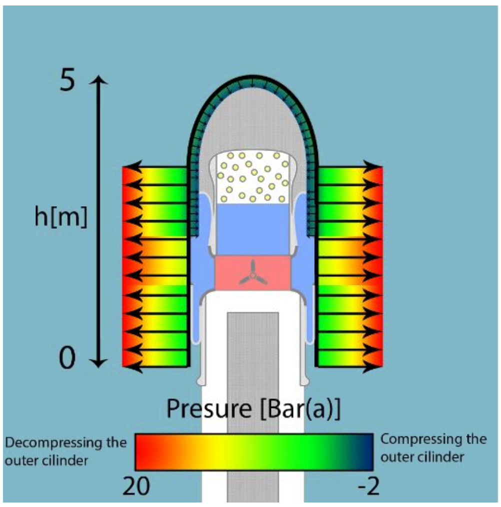


FIGURE 5.2-4: RESULTS OF THE 10MM CARBON STEEL OPERATIONAL LOAD CASE. FLOATER/HULL IN TOP POSITION (LEFT), AND BOTTOM POSITION (RIGHT) UNDER MAXIMUM OPERATIONAL PRESSURES: THE VON MISES STRESSES IN THE HULL ARE MORE THAN TWICE AS HIGH WHEN IN LOWER POSITION, DUE TO THE INTERNAL WATER PRESSURE TRANSMITTED BY THE MEMBRANE.

<u>Fatigue load case</u>

The internal and external pressures on the hull are alternating, both due to varying submergence and mainly the vertical discplacement of the hull along the inner cylinder via the membrane. The alternating pressure will cause the material properties to change. The frequent variation of several bars during one cycle in the contact area is sketched in Figure 5.2-5.



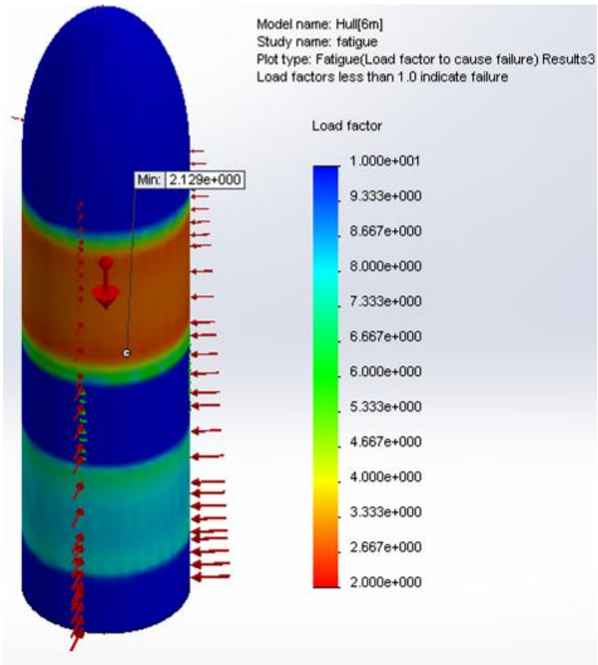


FIGURE 5.2-5: ILLUSTRATION OF FATIGUE LOAD CASE (LEFT) AND PRELIMINARY RESULTS (RIGHT).

5.3. Wave loads: preliminary motion analysis

As mentioned above (see section 0), dynamic loads from waves are not considered to make a critical difference in terms of the structural integrity of the Symphony device, and preliminary strength estimates for the hull where obtained by estimated (pessimistic) input values for potential hull submergence.

During the initial structural analyses, it has been identified that any further calculations should be preceded by a motion analysis of the Symphony device, as the main variable (external/environmental) parameter with relevance for the structural design is the position of the device in the water column (level of submergence; tilt).

This section presents the methodology for the preliminary motion analysis of the Symphony floater under wave loads. The final objective of this methodology is to provide a preliminary estimation of the hydrodynamic loads. The methodology presented here is based on the following assumptions on the system:

- Hydrodynamic loads:
    - It is assumed that linear potential flow theory is applicable. This is a strong assumption for the Symphony system in large waves, as this may result in large motion amplitudes. Also, in extreme sea states, the Symphony floater's size becomes smaller in comparison with the wave. Diffraction/radiation might not be the dominating hydrodynamic contribution in such cases.
    - Viscous drag will be added using relative velocity Morison formulation. This formulation relies on the drag coefficient, the value of which needs to be calibrated with experimental measurements. An estimated value from standards will be used here.
- Mooring loads:
    - It is assumed that quasistatic mooring theory applies. This is a strong assumption considering the Symphony's probable mooring system. As the dynamics of the lines will not be modelled, dynamic effects such as snap loads will not be considered in the analysis.
    - The only external loads considered on the mooring lines will be weight and buoyancy. Neglecting hydrodynamics on the mooring system might also be a strong assumption in the case of the Symphony system.

At a later stage of the system development, a more complete methodology for hydrodynamic analysis, motion analysis and mooring analysis should be elaborated, using, for example, experimental results and dynamic mooring model and/or CFD if relevant.

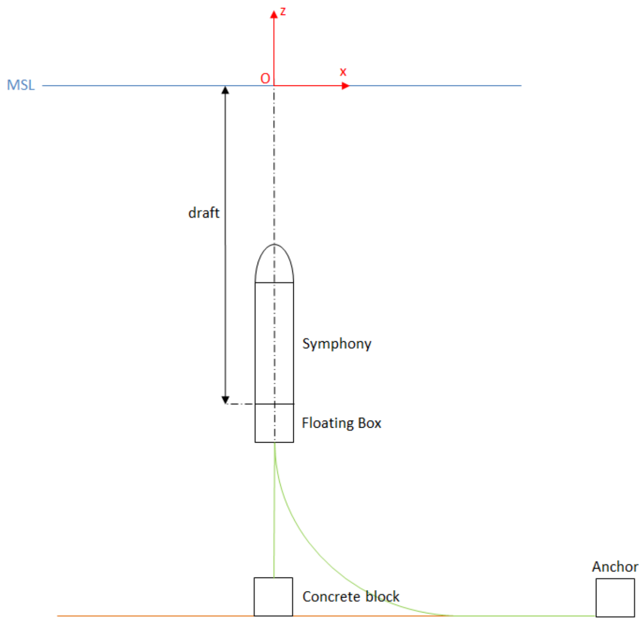
Modelling strategy

Software

Symphony floater motions will be computed using InWave, INNOSEA's in-house multibody offshore system software. InWave mechanical solver is a nonlinear time domain solver. Hydrostatic loads are calculated using an instantaneous hydrostatic pressure integration. Hydrodynamic loads are calculated using a combination of linear potential flow theory and Morison drag equations. Mooring loads are calculated with a quasi-static mooring model integrated in InWave. Hydrodynamic pressures are finally calculated in post-processing of the motion analysis.

Design Calculation Cases (DCC)

In this section, two design calculation cases were defined by TeamWork for the motion analysis carried out by INNOSEA.



THE DCC 1 CONFIGURATION IS PRESENTED IN

Figure 5.3-1 below. It corresponds to the operation configuration of the system. The Symphony floater is in the lower position, draft is 39m and the floating box is separated from the Symphony floater. Irregular waves conditions were assumed for this calculation case, defined by an 1 hour sea state with significant wave height Hs = 5m, peak period Tp = 12s and wave direction aligned with one mooring line.

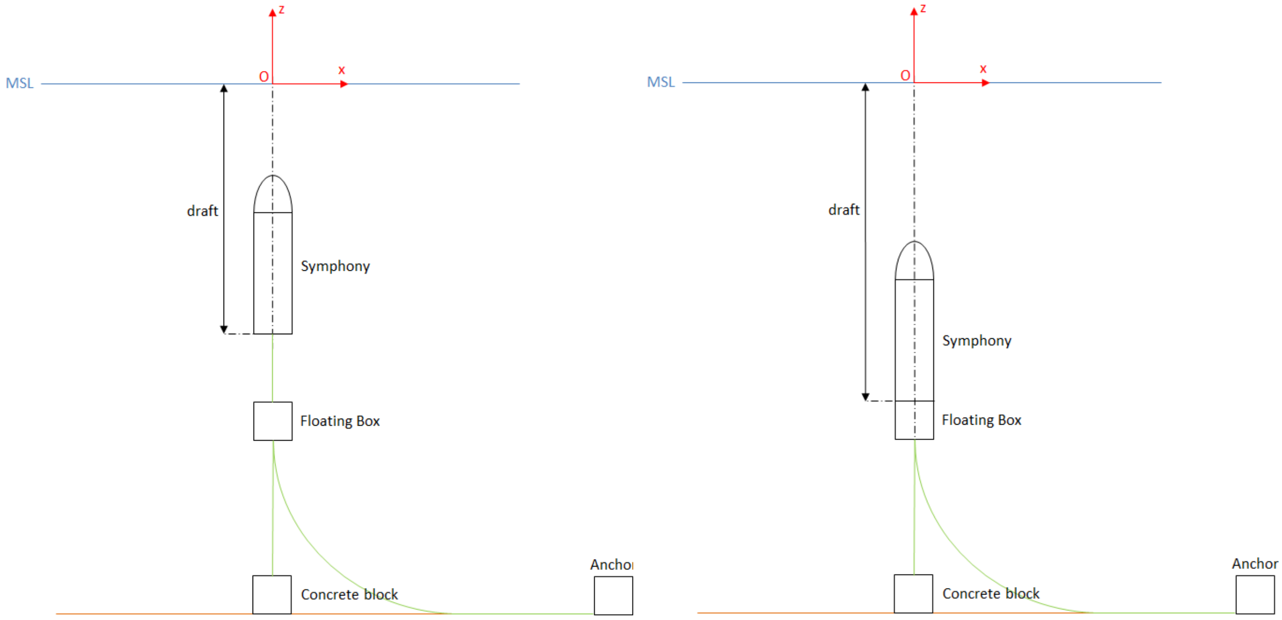


FIGURE 5.3-1 SYSTEM CONFIGURATION FOR DCC1 (LEFT) AND DCC2 (RIGHT)

The DCC 2 configuration corresponds to the survival configuration of the system. The Symphony floater is in the lower position, draft is 50m and the floating box is fixed to the Symphony floater. The wave conditions for this calculation case correspond to irregular waves defined by an 1 hour sea state with significant wave height H_s = 15m, peak period T_p = 18s and wave direction aligned with one mooring line. This maximum wave corresponds to a 100-year design wave in Northern Portugal, according to the scatter diagram of Leixões.

TABLE 5.3-1 DESIGN CALCULATION CASES

DCC	Floater configuration	Mooring configuration: draft (m)	Hs (m)	Tp (s)	Wave direction
1	Lower	39	5	12	In line with 1 mooring line
2	Lower	50	15	18	In line with 1 mooring line

Load modelling

<u>Hydrostatic load model</u>

Hydrostatic force = in InWave is calculated integrating the contribution of hydrostatic pressure over the hull surface.

It can be noted that in the particular case of a fully submerged system such the hydrostatic load on the floater is constant. However, the local hydrostatic pressure will vary with the floater motion due to change of immersion. The terms used for hydrostatic pressure are presented in section 5.2.

Wave load modelling

Hydrodynamic loads on offshore structures are usually computed using Morison formulation or potential flow theory, depending on which physical effect is dominating the wave load (drag, inertia, Froude-Krylov), or a combination of both.

In this case a mix of linear potential flow theory and Morison formulation is considered to compute the wave load. In practice, linear potential flow theory is used and the drag part of Morison formulation is added. Drag is accounted for based on the relative velocity between the Symphony floater and the fluid.

Potential flow theory: Froude-Krylov, Diffraction and Radiation loads

The first contribution of the wave loads is computed using linear potential flow theory. This allows to assessing the following wave loads components:

- The Froude-Krylov load due to the incident wave field;
- The diffraction load due to the diffracted wave field;
- The radiation load due to the radiated wave field.

These loads are assessed in the time-domain by InWave based on a frequency domain hydrodynamic database (HDB):

- Excitation force (Froude-Krylov and diffraction) response amplitude operator.
- Radiation damping and added mass.

The HDB is computed at static equilibrium position of the Symphony floater which is obtained after the hydrostatic analysis.

Main assumptions on which linear potential flow theory is based are:

- Seawater is modelled as an incompressible non-viscous fluid. Viscous effects (e.g. drag) are neglected.
- The flow is assumed to be irrotational.
- Waves are modelled according to the linear Airy wave theory.
- The domain of validity of potential flow theory is limited to large bodies compared to the amplitude of the incident wave, and low steepness waves.
- It is assumed that motions of the body are small in relation to the body dimensions.

Hydrodynamic drag loads

Hydrodynamic loads computed with linear potential flow theory do not account for drag effects. In large waves such as it is the case in DCC2, the Symphony floater size is not "large" compared to the incident waves heights and therefore viscous drag contribution should not be neglected. Therefore, viscous drag is added to potential flow theory. It is modelled based on the relative velocity between the Symphony floater and the fluid.

In InWave, the floater will be modelled as an equivalent cylinder for drag load modelling. This cylinder will be discretized linearly along the cylinder's height in nodes. Only radial drag is considered and axial drag is neglected. On this specific topic, more investigation will be needed at a later stage. The hydrodynamic drag force will be assessed at each node of the cylinder using the drag part of Morison formulation:

$$\overrightarrow{\mathbf{F}_{d_{hyd}}} = \frac{1}{2}\rho_{water} D C_d ||\overrightarrow{\Delta V_N}\Delta \mathbf{V}_N||\ \overrightarrow{\Delta V_N}\Delta \mathbf{V}_N, \tag{5.3-1}$$

where:

C_d is the drag coefficient of the cylinder.

D the diameter of the cylinder

ρ_{water} the seawater density.

$\overrightarrow{\Delta V_N}$ the relative velocity between the fluid and the local node.

Morison theory:

assumes that the body is small compared to the wavelength
assumes that structures are cylindrical.
neglects oscillatory turbulence effects and hydrodynamic interaction between bodies.
is based on empirical force coefficients which are not determined for the Symphony device. They will be estimated at this stage based on [DNV-OS-C205].

Hydrodynamic pressure on the body

A first contribution of the hydrodynamic pressure p_{lin} comes from linear potential flow theory and will be provided on the surface mesh used for potential flow calculations.

Linear hydrodynamic pressures are calculated by taking into account incident, diffracted and radiated wave induced pressures. The incident wave pressure depends only on the incident wave field. The diffracted wave pressure depends on the incident wave and on the Symphony floater's geometry. The radiated wave pressure depends on the Symphony floater's geometry and motion. As this quantity depends on motion, the motion analysis presented here is required to compute the total dynamic pressure field:

$$p_{lin} = p_i + p_{diff} + p_{rad}, \qquad (5.3\text{-}2)$$

where:

p_i is the incident wave induced pressure.
p_{diff} is the diffracted wave induce pressure.
p_{rad} is the radiated wave induced pressure.

Hydrostatic pressure will be provided on the potential flow mesh if required by the structural analysis. In addition, drag force at nodes of the linear discretization along the height of the floater hull can be provided.

Mooring loads

A quasistatic mooring model will be used to model the mooring system. This model is neglecting some physical phenomena that might be important for Symphony's mooring system. Quasistatic mooring theory assumes that mooring lines are at static equilibrium at all times. Therefore, the equilibrium of the lines is solved and the mooring load is deduced. The dynamics of the lines is not taken into account in the quasi-static model. This is a strong assumption for Symphony's mooring system. In particular, snap loads that might occur in vertical mooring lines will not be captured correctly with this model.

Also, hydrodynamic loads on the mooring system are neglected. These loads might be important in the case of the Symphony device. In particular, hydrodynamic loads on the intermediary buoy and drag load on the mooring lines will be neglected. This issue will have to be investigated in more detail in a later stage. Friction of the mooring lines will also be neglected at this stage. This issue will also be investigated in more detail in a later stage. Additional assumptions of the quasi-static mooring model used in InWave are:

- The transverse section of the line is assumed constant.
- The line is assumed to be infinitely elastic with constant stiffness. Therefore, line tension is assumed to be smaller than line material yield stress.
- Flexion stiffness is neglected.
- Line torsion is neglected.

Output of the motion analysis

The results of the motion analysis will be provided as time series of one hour for each DCC and will include:

- Motion of Symphony floater.
- Linear hydrodynamic pressure on the surface of the hull of Symphony floater.
- Linear drag force at nodes of the linear discretization along the height of the Symphony floater.

6. POTENTIAL CHALLENGES

6.1. Structural engineering challenges

Three key challenges for the structural design can be anticipated at this stage:

- Vertical position. Impacts with the end stop- can potentially be seriously damaging. A horizontal design with two counter-acting floaters is under consideration (see section 0), and is likely to be the preferred choice for future developments. All components developed in WETFEET and the controls could be integrated into such an arrangement. The control cocoon might have to be embedded into a different shape, but the key developments (wet connectors, controls, connections/releases, air/water circuits) would be transferable. However there are some uncertainties about such a horizontal arrangement, and additional RTD steps appear to be required.
- Span width of pressure-exposed areas/plate sections of the hull and the internal cylinder need to be made quite small, in order to counter the large differential pressures in a flexible manner. This drives material costs up and the manufacture process more complex.
- Material choice. Steel as material is expensive and heavy, especially for a large-scale vision. Although reinforced, and in particular pre-stretched, pre-fabricated concrete pieces could be generally an option, the same drawback remains for the weight issue. Composite materials like fibreglass are under consideration, and the preliminary structural analysis (see Figure 5.2-2) indicated reasonable material thicknesses requirements, yet very likely implying costs similar to those of steel. They would seem especially suitable being easier to shape and also, once applied the right resins, seawater resistant. On the other hand, the connections of the membrane, potential local failure zones, could be more vulnerable if manufactured in fibreglass.

6.2. Environmental impacts

Being a fully submerged device, the Symphony is intrinsically less exposed to environmental and accidental loads (floating debris, vessels), and as such in principle less risks for spillage or destroyed and abandoned WECs exist.

On the other hand, it could be argued that being submerged the device is a higher potential threat for maritime traffic, especially if, due to a failure or extraordinary sea states the device does not have the planned clearance of several meters. Potentially vessels could collide easier than with floating devices, due to visiblility, including radar. In such cases floating debris and/or spills of noxious substances cannot be excluded. Certification and appropriate site marking efforts, as well as intrinsic safety design for the technology need to be implemented to prevent such situations. Probably an Exclusion Zone would be needed and this will need to be marked with cardinal buoys.

Even in the case of a collision or destruction of the device it is unlikely that a major threat to the environment is posed, as the internal working fluid inside the Symphony is water.

Major impacts may be derived from marine operations (noise, sea bed disturbance) for mooring installation, as well as fuel consumption throughout the manufacture, transportation and inspection/maintenance. All these impacts however are generic to marine energy devices, and at present stage of development there is no apparent reason to reinforce one specific topic for Symphony's development.

The breakthrough components themselves and their potential impacts in large-scale installations, will be considered more closely in considerations about the EIA (Environmental Impact Assessment) in WP7. As explained more detailed in [Del. 2.1], a reasonable approach at this stage could be the preliminary identification of stressors (features of the environment that may change with project implementation) and receptors (ecosystem elements with potential for some form of response to the stressor), which is tentatively presented in TABLE 6.2.1.

TABLE 6.2.1. PRELIMINARY IDENTIFICATION OF KEY STRESSORS AND ENVIRONMENTAL RECEPTORS OF THE BREAKTHROUGHS CONSIDERED FOR SYMPHONY.

Breakthroughs	Key stressors	Key receptors
Structural membrane	Alteration of water quality (corrosion of new materials)	Marine mammals Fish Benthos
Continuous submergence: the control cocoon	Collision (visibility)	Marine mammals Fish
Shared moorings	Collision Entanglement Artificial reef effect	Marine mammals Fish Benthos Sediment dynamics (seabed morphology)
Dielectric elastomer generators	Alteration of water quality (corrosion of new materials)	Marine mammals Fish Benthos
Electro- mechanic PTO	Noise	Marine mammals Fish

6.3. Cost implications

The large swept volume that derives from the necessity of increasing Symphony's length (see Figure 5.1-1) due to (too) heavy components, is possibly the major obstacle of the present design. However it is suitable for the development of the WETFEET breakthrough components, which is the focus of this project. Each of the components structural membrane, turbine and control cocoon can all significantly contribute to more reliable and thus more cost-effective wave energy devices.

Especially the water turbine, if proven in WETFEET as technically feasible, could turn out to be a very simple, rugged PTO turning the conversion from reciprocal linear motion into circular motion for a regular generator significantly less expensive than existing PTOs, at the same time avoiding any end-stop related issues.

The membrane as being the end stop of Symphony, can contribute to not having to over-dimension this safety feature in comparison to the rated power output of the device. The rubber material is straight-forward to manufacture and abundant, without much stock variations in foreseeable time, hence with no significant supply chain issues associated to its future large-scale development.

The control cocoon is being developed to reduce substantially any maintenance cost and downtimes of WECs when in commercial operation.

In a very initial, rather qualitative analysis, the expected effects on the levelized cost of energy (LCOE) of each of the breakthrough components is indicated in Table 6.3.1. As explained more in detail in [DEL 2.1], the concept of LCOE is increasingly considered an apropriate tool for comparing the unit costs of different technologies over their economic life, and is defined as the total lifecycle costs (i.e., the sum of all capital costs and lifetime operation and maintenance costs, discounted to present value) divided by the electricity generation to grid accumulated throughout the technology's lifetime (also discounted to present value).

In addition to a more comprehensive description in Deliverable 2.1 of the WETFEET project [Del. 2.1], the concept of LCOE will be introduced in detail in WP7, in the context of more detailed analysis of the impacts of the breakthroughs to the LCOE.

Breakthrough concept	Expected impact on the AEP	Expected impact on the CAPEX	Expected impact on the OPEX
Structural membrane	0	⇩	⇩
Continuous submergence: the control cocoon	0	⇧	⇩
Dielectric elastomer generators	0	⇧	⇩⇩
Shared moorings (slack)	0	⇩	⇩
Shared moorings (rigid)	⇧	0	⇩
Electro- mechanic PTO	⇧	⇩	⇩

TABLE 6.3.1 EXPECTED IMPACTS OF THE DIFFERENT BREAKTHROUGHS ON THE LCOE COMPONENTS AEP (ANNUAL ENERGY PRODUCTION), CAPEX (CAPITAL EXPENDITURE) ANS OPEX (OPERATIONAL EXPENSES)

A consideration of cost impacts per component like the above must be considered very carefully in case of the Symphony, as one one hand no tangible rerference case exists. On the other hand, some of the breakthroughs are required for making the Symphony concept as such feasible (structural membrane, control cocoon), so neither an impact on AEP (annual energy production), nor on CAPEX (Capital Expenditure) are straight-forward to estimate. Most important impacts in this phase of the sector's development however is the operational issues, in which all of the breakthrough components are expected to have a positive impact.

As final note, very preliminary cost estimates for serial utility-scale Symphony production will lie in the range of 0.15 € / kWh, if all innovative compenents are chosen properly and successfully implemented.

7. CONCLUSIONS AND FUTURE WORK

In this deliverable, preliminary design and breakthroughs integration considerations were depicted with respect to the development of a Symphony WEC. The potential challenges raised in the previous chapter will serve as a basis on the decision to select the most appropriate configurations of the Symphony for each breakthrough.

Following this work, an iterative process between the structural loads calculation and the structural analysis method will occur in order to gather sufficient information on the structural challenges associated with the three geometries of the reference case Symphony. This will mainly serve to find the best trade-off between material costs and properties, and desired geometry. The own weight has shown to be an issue for the desired choice of dimensions. This and other factors may lead at a later stage to full-scale Symphony visions in horizontal configurations, potentially on rigid bases connecting several units.

Beyond the conceptual and preliminary analysis reported in the present document, the following future steps will be undertaken to further develop the breakthrough ideas related to the Symphony:

- Hull material and structural membrane: the first approach was to use steel, but in a second phase a composite structure for large parts of the structure to guarantee for thee integration of all components. Results of the motion analysis will fed back into the structural assessment of the hull (Task 2.4), and connection of the structural membrane will be defined (WP3).
- Control cocoon: the electrical connections will be designed and the final layout confirmed with available space (task 2.4), after dimensions and weights of auxiliary components (generator, tanks, pumps, pipings, controls etc.) are determined, and an engineering design of a cocoon for the 1.5m diameter device will be finalised (WP3).
- Dielectric elastomer generators: after dtermination of the most promising DEG layout in Symphony (Task 2.4), a simplified model of the proposed architectures for Symphony featuring DEG will be incorporated in the existing time domain model of Symphony, and iterations with the DEG development in WP5 will be performed.

The other two breakthrough concepts, water turbine and array breakthroughs, considered in this report will not be the object of further work within the frame of this WP, as the status of the preparatory work is sufficient to initiate the dedicated tasks in work packages 4 and 6, respectively.

The priority of this document and the subsequent Del. 2.3 is to outline the integration of the breakthroughs into the Symphony, and to anticipate issues and benefits related to it. Unlike the OWC spar buoy, the Symphony is an unprecedenced WEC concept, which has to be developped as a global system alongside the breakthrough components, some of which are vital to this functioning principle. The only resemblance of the original Archimedes Wave Swing concept to this end was the fact of being a submerged varing pressure device. That concept had been abandoned due to reasons that are expected to be addressed largely by the structural membrane. Also structural solutions, PTO and moorings of Symphony differ fundamentally, which is why in case of Symphony a clear distinction of breakthrough component development and global device development is impossible, due to the lack of reference cases.

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