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WETFEET

Deliverable 3.3 Feasibility assessment of Symphony stuctural membrane as a negative spring and replacement for mechanical components in other heaving WECs

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ABSTRACT

This report presents Deliverable 3.3 of the WETFEET H2020 project, "Feasibility assessment of Symphony structural membrane as a negative spring and replacement for mechanical components in other heaving WECs".

The work builds on former Deliverables 2.1 to 2.3, where the negative spring in a OWC spar buoy and in particular the structural membrane for the Symphony as negative spring, end stop and bearing are analysed in detail. Further, it takes into account the results of WP3, in particular the detailed design and manufacture of the prototype structural membrane for a 1.5m diameter device. The potential implementation of the Symphony 'bellow frame' module into other heaving WECs has been given increased interest in the course of the project, as it appears to be a promising approach to solve spring and end-stop functions in general, by providing an almost identical module.

In this document, the existing options for providing a negative spring component, or more precisely, a spring component fully adapted to the needs of heaving WECs are discussed, and the function of the Symphony bellow frame / membrane system is recapitulated. Its use is extended to other heaving point absorbers, by eventually replacing other (existing) components. Exemplary calculations for a simplified design case of a 6m diameter WEC are presented. Engineering issues and practicality considerations complete the feasibility assessment of implementing the Symphony membrane system in generic heaving point absorbers and OWCs.

List of Acronyms

AWS	Archimedes Wave Swing
OWC	Oscillating Water Column
PTO	Power Take-Off
WEC	Wave Energy Converter
WP	Work Package

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.

Following this approach, the WETFEET work programme is organized in two different work streams, one for an OWC spar buoy, and one for the submerged Symphony WEC (Wave Energy Converter). For each of these devices, numerical and conceptual assessments of formerly identified key breakthrough components and their perspectives were elaborated in WP2 and presented in Deliverables 2.1 – 2.3 ([1, 2, 3]).

The purpose of this document is to explore the integration of the development of the structural membrane for the Symphony WEC with the known advantages of (floating) heaving wave energy devices.. The key findings of these considerations have been published in the EWTEC 2017 conference [4].

1.2. Heaving point absorbers

There are many ways to convert the energy from the waves. Many of these have been studied and prototyped and even tested at real sea conditions. Not many have succeeded to be successful at the end. However lessons were learned. WETFEET focuses itself on the development of breakthrough technologies.

All technologies looked at within WETFEET are within the category of heaving point absorbers. Although other technologies might work, the heaving point absorber shows a capability to have a high power to mass ratio. To achieve this high power to mass ratio, the device should not only be a heaving point absorber, but it should also be able to control its motion to keep a synchronicity with the wave (keep it in phase). As power is force times velocity, the motion should be controlled in a way that velocity is on its maximum as the wave force is at is maximum.

One of the critical components that is developed within WETFEET is the structural membrane. This membrane is developed for the Symphony device, and is described in Deliverables 3.6 and 3.7, but seems to be applicable in other devices as well, and has the potential of having a breakthrough nature for a number of different technologies.

1.3. Explaining the function of the structural membrane in general, and more specific in a floating device

The membrane is a structural part of the device and it has three functions:

1. a bearing: as it guides the moving part along the central part;
2. a seal: as it separates the outside to the inside;
3. a piston: able to apply a vertical force between the outside and the central part.

As an addition to the third function, the vertical force application, there are three possible applications in which this vertical force is applied.

A. As a force to counteract the force applied by the waves. This force can be used to act as an end stop. All heaving devices have a limited stroke of operation. Beyond this motion the system should run into an end stop. This is a section in which the reaction force increases over a short distance. Whit the only purpose to stop the motion before it reaches the physical limits of the structure and gets destroyed.

B. Energy captured in the mechanical energy of the moving floater.

C. As a force that is related to the vertical position in normally such a relationship of force related to position is called a spring. In the case of the structural membrane this force depends on the two surfaces, see the figure below.

The membrane is squeezed between an outer and inner cylinder. By designing the gab size or distance between the cylinders, the membrane can have larger or smaller 'bellows' on the top or bottom side. In the left picture the larger membrane surface is on the top side, while in the picture on the right, the large gap is on the bottom side. Only the pressure acting against the curved area of the membrane (where the membrane is not pressed against either cylinder) is an active force in the system. So the gab differences result in a resulting force up or down.

This result is a vertical resulting membrane force between the inner construction and the outside on the left, pointing upwards, while on the right it points downwards.

In the operation of the devices these resulting membrane forces, counteract the hydrostatic forced. For the left construction, this is downward as this is a submerged construction. For the right construction this is upwards. As both the outside hydrostatic forces and the membrane forces depend on the vertical position of the outer construction, the resulting vertical force is position depending force. In both constructions the weight of the construction is important as well, but is constant.

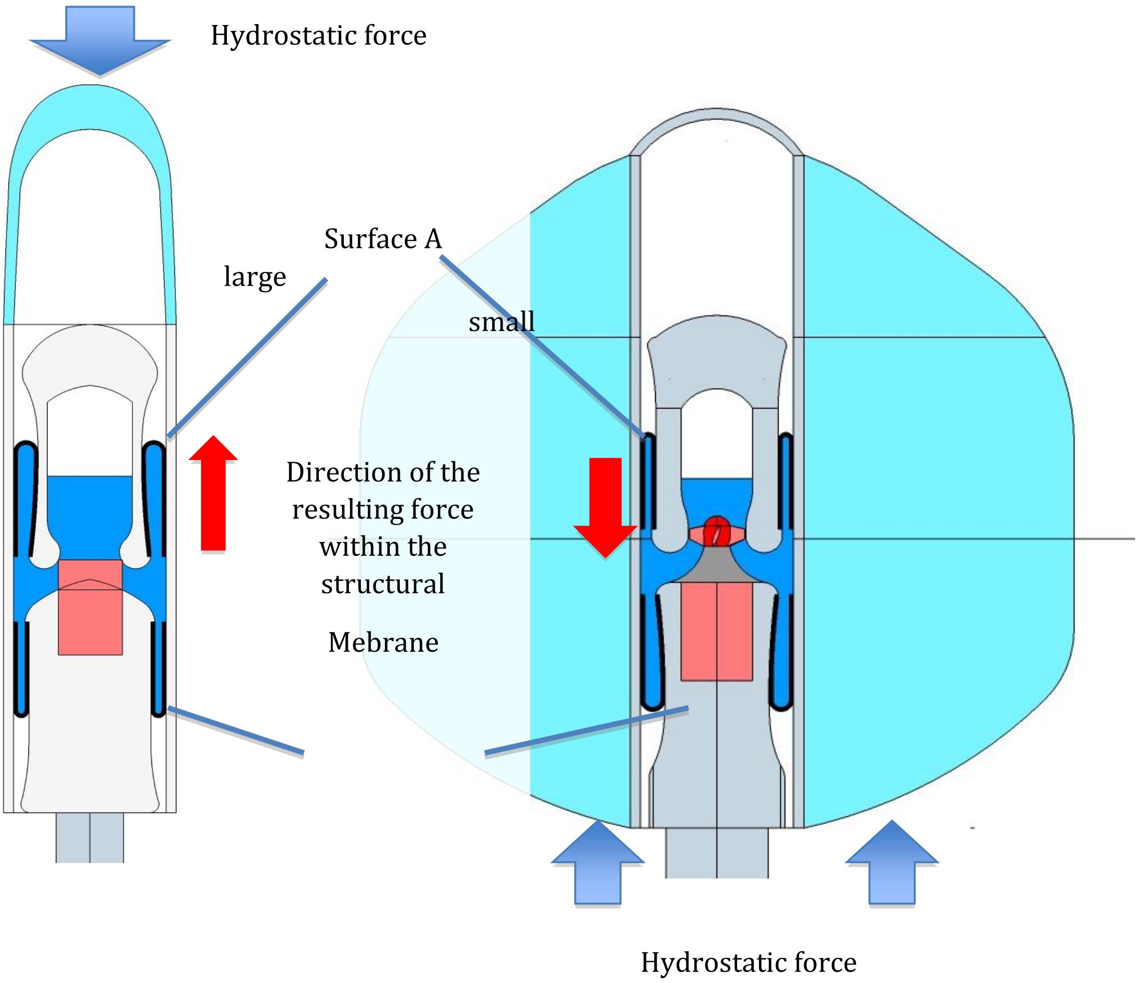

FIGURE 1: MEMBRANE CONSTRUCTION AND RESULTING FORCES IN RELATION TO THE GAB WIDTH.

The membrane is squeezed between an outer and inner cylinder. By designing the gab size or distance between the cylinders, the membrane can have larger or smaller 'bellows' on the top or bottom side. In the left picture the larger membrane surface is on the top side, while in the picture on the right, the large gap is on the bottom side. Only the pressure acting against the curved area of the membrane (where the membrane is not pressed against either cylinder) is an active force in the system. So the gab differences result in a resulting force up or down.

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Variation of acting surface

The force on the membrane is defined by the surface the inner pressure acts on and the surface it acts on. As this pressure is substantial (up to 25 bar), the force can be of big influence. The pressure is maintained by the pressure in the gas volume in the inner cylinder added pressure vessel. The membrane moves during the motion of the outer hull from the inside to the outside, and stretches itself to the diameter. Because the inner structure allows the membrane material only to stretch in radial direction it can adjust to the shape of the cylinders in which it is guided. Shaping these cylinders defines the width of the gap and as such the force the membrane applies to the outside hull. It is important to understand this principle to be able to use the features of the membrane in its full extent.

Pressure variation

As the outer hull is displaced, the total membrane volume (the volume between the cylinders) is changing. Not all liquid can flow from the large gap into the small gap. Some of the liquid will flow into the central vessel. As this compresses the gas, the pressure will change. To define the resulting force acting on the membranes between inner construction and outer hull, the changed pressure should be taken into relationship.

More to the vertical force generation of the membrane

As described, the capability of the membrane can be used to define end stops, to define a position dependent (spring) force and to take off power from its motion.

Although the membrane is seen as an efficient tool to be used as a power take-off, other options can be considered as well.

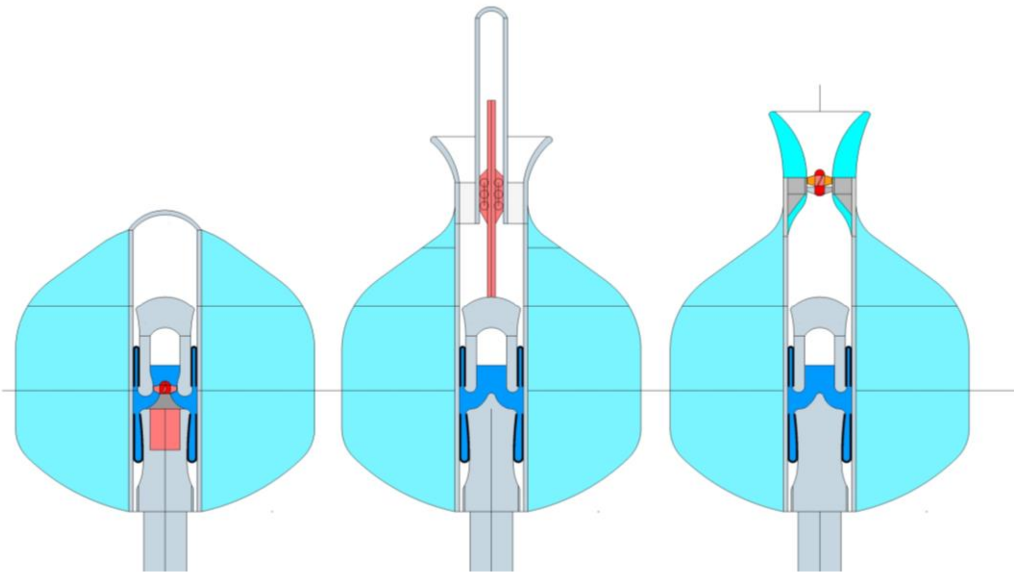


FIGURE 2: DIFFERENT OPTIONS FOR EXTRACTING ENERGY WITH USE OF THE MEMBRANE.

In the figure above a structural membrane is integrated in a floating body. On the left a turbine placed in the water flow between the membrane and the central pressure vessel is used as a power take off. In the middle the flow inside is unrestricted and the energy is taken of with a rack and pinion (CorPower reinvented) on the right an air turbine is used. Possible other options can be considered as well like hydraulic cylinders or a linear generator. After considering all options, Symphony has developed a special turbine but if the turbine is not working well enough other options are possible and the development of the structural membrane is still adding its values.

Note:

In all cases above there is a tension leg to the seabed connected to the inner structure. This is needed to add the force to position dependent characteristics to the floating device. Therefor this a fundamental different device than a spar buoy as developed within the project as well. A tension leg can be seen as a disadvantage to floating devices as large waves might make the leg go slag causing huge snapping forces and possible damage. The spar buoy does not have this disadvantage. As it is intestinally moored in a way that it can handle large motions without vertical tension in the mooring. If however the tension leg should prove reliable as for instance foreseen in the Corpower device the structural membrane might add characteristics that can synchronize the device to the waves and increase a much higher efficiency. This is explained in the next chapters.

1.4. The importance of the spring characteristic

As indicated before, the phase shift between the moving body and the waves is a major criteria to convert energy from the waves. This means velocity and wave force should be in Phase. Below three examples are given (half a wave cycle) the blue line gives the wave elevation the thin line gives the position the dashed line the velocity and the fat line the power. In the middle the phase shift between wave and position is optimal. In both others the multiplication of wave force times velocity is not only lower, but on an average we see partly positive and partly negative power. This means another source of energy is acting on the body as well. As the devices always act as a damped mass- spring system, we see here the effect of mass and spring once in phase mass and spring forces cancel each other out. In the pre-phase, the spring force (buoyancy) is dominant. In the after phase the mass force (weight) is dominant.

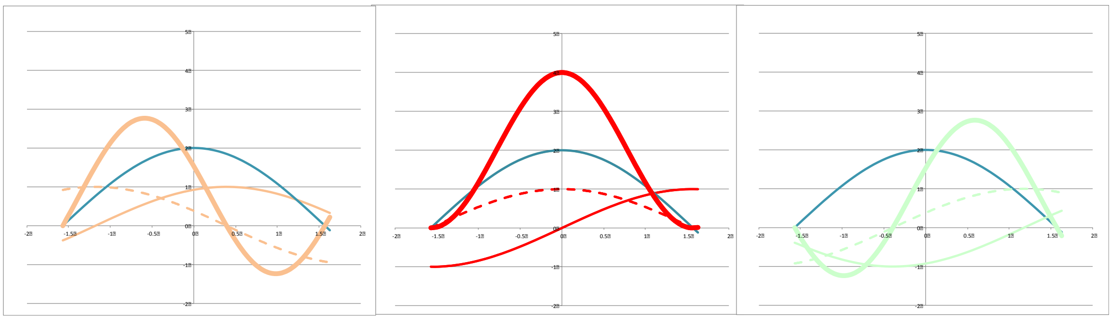
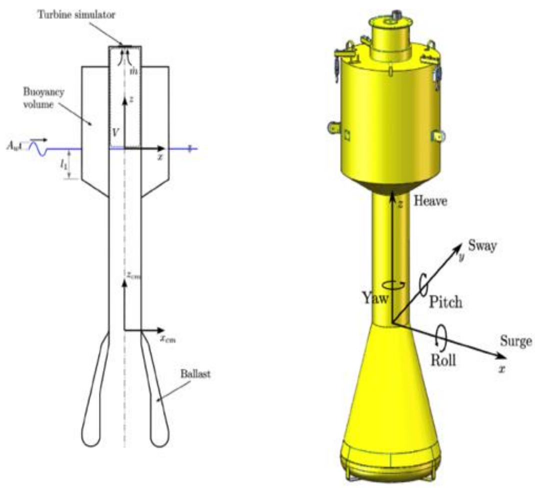


FIGURE 3: PHASE DEPENDANCY. THE WAVE IS INDICATED IN BLUE, THE POWER IN THE BOLD LINE, THE POSTION IN THE THIN LINE AND THE VELOCITY IS DOTTED. LEFT: PRE-PHASE, MIDDLE: IN PHASE, RIGHT: AFTER PHASE.

Dynamic behaviour

As indicated above, it is important to maintain in phase with the waves. This is only possible if the mass and spring forces cancel each other out during motion. In dynamic analysis this is called resonance. By defining the natural frequency at the wave frequency, the system will move in phase with the wave.



For a design of a buoy to fit this purpose normally the mass is increased, as the spring force is determined by the variation of buoyancy. By increasing the volume underwater and equally increasing the mass by the mass of displaced water volume, the spring stays constant these devices have a large underwater body. Such a device can be a so called spar buoy.

Another way to synchronize a buoy is by weakening the spring. A design that follows this principle has an mechanism inside that produces in its middle position a zero force, but as the mechanism moves away from the force, this force increases and points away from its equilibrium position. Such a construction is applied for instance by CorPower. A mechanism with this kind of characteristics is **called a negative sprin**g.

Since the structural membrane is able to apply a force in any direction by shaping its guiding walls. This construction should be able to provide a negative spring characteristic as well, and could add to a buoy the synchronization capabilities which makes it possible to produce more power. There is evidence that a 300 – 400% efficiency improvement can be achieved this way [4].

The following chapters will provide a more in-depth explanation.

2. Point absorbers and resonance

Heaving point absorbers can convert more power from ocean waves if they resonate to the prevailing wave period. In practice however, the natural frequency of most buoys is not tuned at wave frequency, due to their dimensions. With power ratings in the range of hundreds of kilowatts and several meters of diameter, floating heaving buoys e.g. have a natural frequency far above the range of typical sea states, due to a very high positive spring force resulting from buoyancy. This makes it necessary to tune such buoys by either adding a negative spring or actively restraining their movement (e.g. via PTO), or by increasing their mass [9].Partly related to this is the potentially biggest challenge for heaving point absorbers, the end stop: on the end of the "useful stroke" along which energy is produced, massive forces may occur due to a sudden braking of the motion. This effect and its related engineering challenges increase for resonant devices. Although not focus in this Deliverable, this aspect is intrinsically part of the discussion at some point.

Part of the Symphony development has been a unit that can be integrated in heaving wave energy devices to increase their power capture abilities by enabling resonating behavior. The device can be adjusted to different applications, and contribute both to the tuning of the device and provide an intrinsically safe end-of-stroke system. A basic, non-resonating heaving wave energy converter, is formed by a (large) floating body, moving up and down with the waves. The energy is converted by slowing down the motion of the body that follows the water surface. The stroke of the movement is limited to the height of the wave. Such systems are very limited in their efficiency as the interaction with the incoming waves is very small.

Research [5] shows that the efficiency of such a buoy can be improved by increasing the stroke of the floating body, creating a so-called resonant "point absorber".

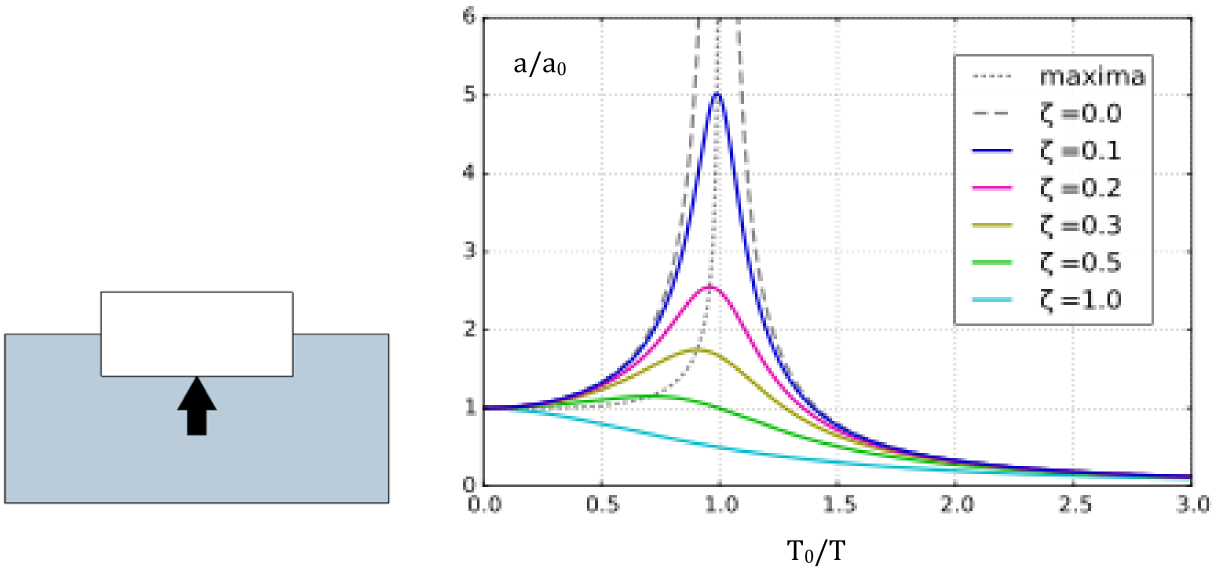


FIGURE 4: FLOATING BODY (BUOY) AND PREDOMINANT HEAVING FORCE (LEFT), AND DYNAMIC RESPONSE AT RESONANCE (RIGHT)

A floating body (4, left) acts as a mass-spring system; when displaced vertically, the upward directed force changes direction, ultimately pushing the body back towards its equilibrium position. The largest motion in a wave can be observed when the natural frequency of this system is equal to the frequency of the incoming wave.

Figure 4, on the right hand side, shows the characteristics of a damped mass-spring system. The hydrostatic spring S of the buoy depends on the floatation area (the cross-cut area of the body at the water free surface level). In the following, a simple cylindrical floating body is assumed:

$$S = \rho \, . \, g \, . \, A \; [N/m] \tag{0-1}$$

where ρ = specific mass of (sea) water

g = gravitational constant [9.81 m/s]

A = cross sectional area of the cylinder

The mass M of the buoy equals the mass of the displaced water,

$$M = \rho \, . \, A \, . \, d \;\; [kg] \tag{0-2}$$

where d is the draft of the cylinder

Neglecting added mass (i.e. the mass of water that is put in motion due to the body motion) the resulting resonance period T is computed as,

$$T = 2 \, . \, \pi \, . \sqrt{\frac{M}{S}} = 2 . \, \pi \, . \sqrt{\frac{d}{g}} \tag{0-3}$$

The power capture is highly dependent on the wave force and the motion of the capture surface during operation. The capture surface is the surface of the body that is able to disturb the surrounding water by applying a force on it. In the case of Fig. 4 it is the submerged horizontal surface where the arrow points. For an optimal design of a point absorber we can therefore assume:

- The capture surface must be as close as possible to the water surface, as the wave induced pressure decreases very fast with the distance to the free-surface.
- The system natural frequency must be as close as possible to the wave frequency.
- The mass must be as low as possible to enable response to a wide spectrum of waves and also to reduce the mooring forces.

1.5. The Negative Spring in WECs

Heaving wave energy converters (HWEC) are a very promising solution for wave energy extraction with many different technologies being developed based in this principle (CorPower, Wedge, OWC, etc.). However, due to the high hydrostatic spring effect (resulting from the unbalance of the weight and buoyancy when the converter is oscillating – and not at its equilibrium position) these systems tend to be very rigid, with resonance frequencies higher than those of the incoming waves, which results in less performing systems. Negative springs in general are mechanical systems that are unstable when deviated from its equilibrium position and can be used to reduce the stiffness of HWEC and thus increase significantly their performance. An example is a device composed by two aligned pre-stressed springs, as the wave spring used by CorPower. Another alternative, which is being studied in the WETFEET project, is a submerged non-rigid air volume, as its volume and the corresponding buoyancy will be reduced with water depth.

The resonance period of a wave energy converter (WEC) is given by eq. (1.2-3), where, in the general case S is WEC total stiffness, usually composed by the hydrostatic spring as given by (1.2-1) and by a usually much smaller spring contribution from the mooring lines. If we add a negative spring, the total stiffness of the WEC became smaller and the WEC's resonance period becomes as close as we want to the incoming wave period, thus increasing very significantly energy extraction (e.g. ratios of annual energy production per unit of mass, per unit area or per unit of PTO force).

In WETFEET, the application of a negative spring to a floating OWC and the Symphony WEC has therefore been a central task in the preceding WP2 (System description), where two methods to implement the negative spring in a Spar OWC have beer analyzed. These efforts are summarized in section 2.3. The findings regarding the membrane system of the Symphony as negative spring as basis for the vision to implement it in other devices are summarized in section 3.1.

2. Point absorber types and performance impact of spring

Several developers have implemented methodologies to apply an additional spring to influence the spring characteristics of the system and make it resonant. In the following the effect of this modification towards power capture will be discussed, as well as methodologies to achieve the desired result.

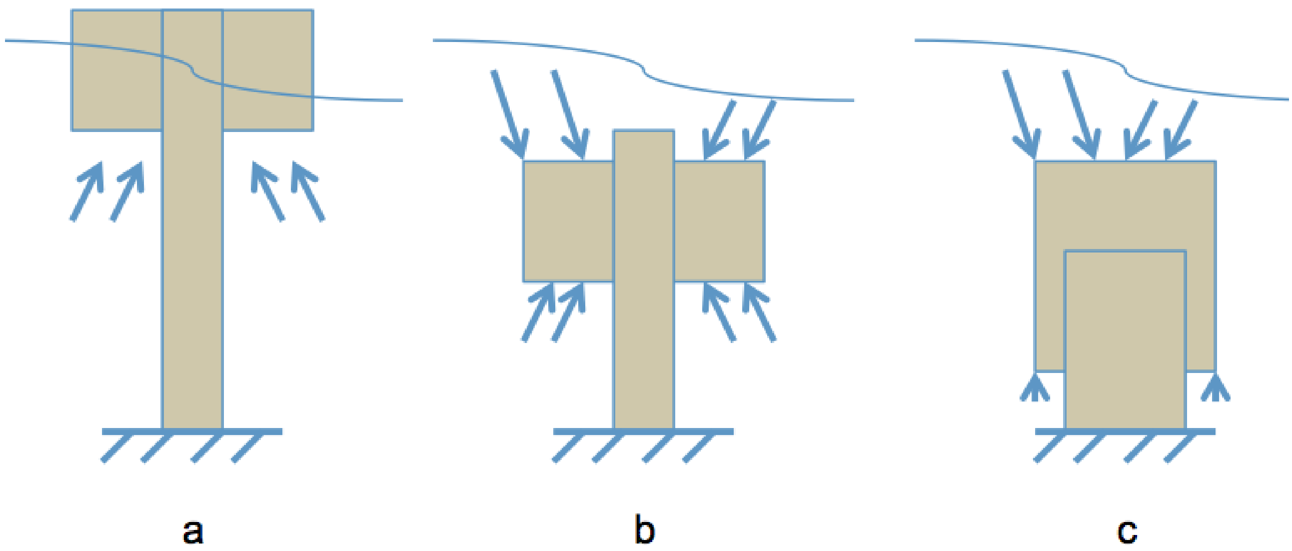


FIGURE 5: THREE FUNDAMENTALLY DIFFERENT TYPES OF HEAVING WAVE ENERGY CONVERTERS

The idealized cases of different heaving wave converters could be described as (see Fig. 5):

a) A surface-floating device with a reaction leg to the seabed. The wave force responsible for the vertical motion acts on the bottom of the device.
b) A submerged device with a reaction leg. The wave force works both on the top and the bottom of the device. As they counteract each other the differential pressure causes the resulting force to drive the motion.
c) A submerged device where the inside structure is connected to the reaction leg. As the inner structure is almost the size of the device itself, the wave pressure on top of the device dominates the driving force.

In the following, the diffraction wave forces (those needed to keep the body fixed under the action of the incident), hydrodynamic damping and added mass are calculated for an exemplary case of all three converter types, and the mass of the devices to keep them (partly) submerged is taken into account. Due to the rather conceptual character of this exercise, both the assumption of dimensions and presentation of calculations are done in a quite simplified manner, based on the formulae presented beforehand.

2.1.Theory and application to different heaving WECs

For a floating body with a limited draft of ca. 5 m the "natural period T" has, independent of its surface, a relatively small value of 5.5s. This is far off of the range of wave periods along the Atlantic Coastline (9-14s), where point absorbers, and wave energy utilisation, in general, is most likely to become relevant. 6 shows that the increased power (and therefore associated stroke) is limited strongly in such systems, when the WEC resonance period T and wave period T_0 differ. Only if T and T_0 match, motions are amplified to above wave height dimensions.

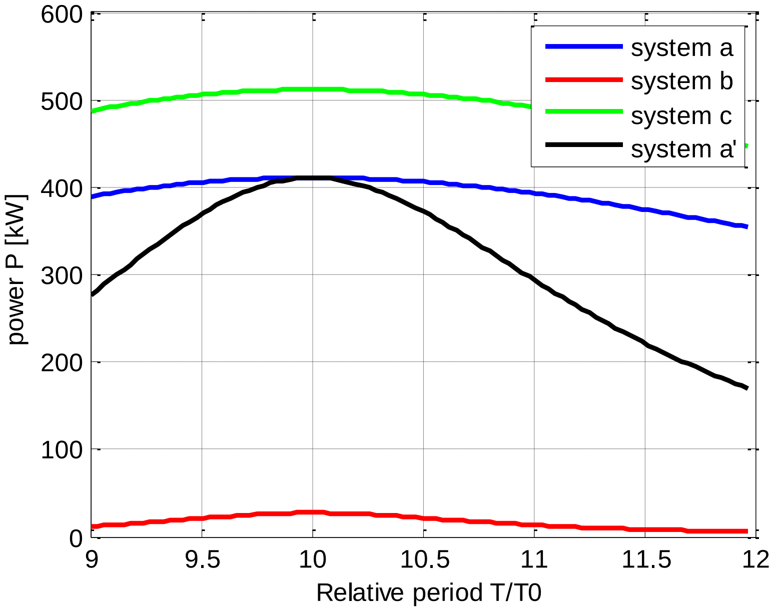


FIGURE 6: POWER OUTPUT. *A,B,C* CORRESPOND TO THE POWER-OUTPUT FROM SYSTEMS IN FIGURE 5 IN A REGULAR WAVE OF 2M (1 M AMPLITUDE), TUNED AT 10 SECONDS BY IMPLEMENTING A WEAK SPRING. *A'* CORRESPONDS TO SYSTEM *A* BEING TUNED BY INCREASING MASS INSTEAD OF WEAKENING THE SPRING.

To change the natural (eigen) period to for instance 10s, the draft of a cylindrical buoy of type "*a*" would have to be increased to approximately 25m, and the mass would have to increase accordingly. This has the disadvantage that the driving wave pressure against the bottom of the cylinder becomes much smaller at this increased depth, requiring much higher strokes (which introduces significant engineering challenges and increases the losses) and narrowing the power versus period curve.

In Figure 7, *a''*and *b'* show the behaviour of the same body dimensions as before without an extra negative spring. The surface WEC (*a*) resonates at 5.5 seconds and has limited power conversion (and motion) at 10 seconds if no negative spring is introduced. For device type "*a*" an optimized negative spring is assumed. For device "*b*" an indifferent system was assumed (very weak spring) and for device "*c*" an internal spring was assumed compensating the negative spring of the hydrostatic force on the top of the device, and tuning it to the resonance frequency. A way how this can be done is explained later in section 3.

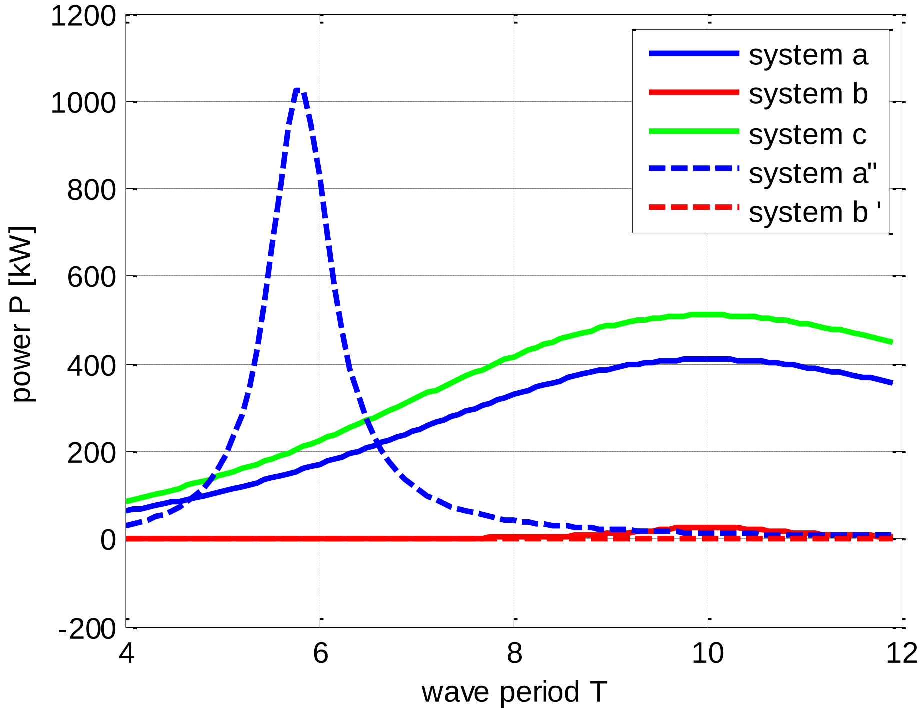


FIGURE 7: POWER OUTPUT (H=2M) AS RESULT OF THE NATURAL FREQUENCY OF THE DIFFERENT TYPE OF DEVICES. ***A,B,C*** **AS DESCRIBED IN FIGURE 5, BUT MADE RESONANT BY ADDING A CORRESPONDING SPRING FOR 10 S NATURAL FREQUENCY.** ***A''*** **AND** ***B'*** **ARE THE ORIGINAL BEHAVIOUR WITHOUT ADDED SPRING.**

For the calculation presented in Table 1, only the behavior on a regular wave of H=2m (1m amplitude) and 10s period is analyzed. This is done to exemplify the effect of a tuned system.

TABLE 1: EFFECT OF RESONANCE: EXEMPLARY CALCULATIONS FOR 3 WEC TYPES

		Calculation of power output		
		a	b	c
dia system	[m]	10	10	10
diameter leg	[m]	3	3	9,5
distance to surface	[m]	5	5	5
maximum stroke	[m]	5	5	5
wave force	[kN /m]	563	87	717
hydr,damp	[kN s/m]	37	5,5	59
added mass	[ton]	246	400	361
Mass	[ton]	366	733	400
spring	[kN/m]	718	0	300
natural period	[s]	5,8	high	10
wave amplitude	[m]	1	1	1
wave period	[s]	10	10	10
stroke	[m]	0,56	1,03	4,55
avg power @10s	[kW]	9,9	<5	511
tuned (resonant) system				
avg power	[kW]	410	27	511
Ratio	[%]	414	nvt	100

The main conclusion from this exercise is that the difference in power output is heavily influenced by the ability of the system to resonate to the wave. In tuned systems the diffraction wave force is in phase with the body velocity resulting in a much higher body motion and velocity and thus a much higher power output can be obtained (up to more than 400%).

In the following the possibility of tuning devices by adding a negative spring is discussed further. Other options to optimise are reactive control and latching control. A comparison, of these options is not part of this Deliverable.

In device c, in the previous discussion an internal spring is assumed. In the past the Archimedes Wave Swing was build and tested at full-scale [8]. This device uses an internal air volume as a spring, counteracting the hydrostatic force on the top of the system. This resulted in a very week spring, which made this device resonant to the waves in a wider range of periods. The change of pressure however does not follow the displacement in a linear way, which results in de-tuning of the system as it moves away from its equilibrium. Figure 8 shows the principle of operation and the effect on the natural period for the Archimedes Wave Swing system with 10m diameter.

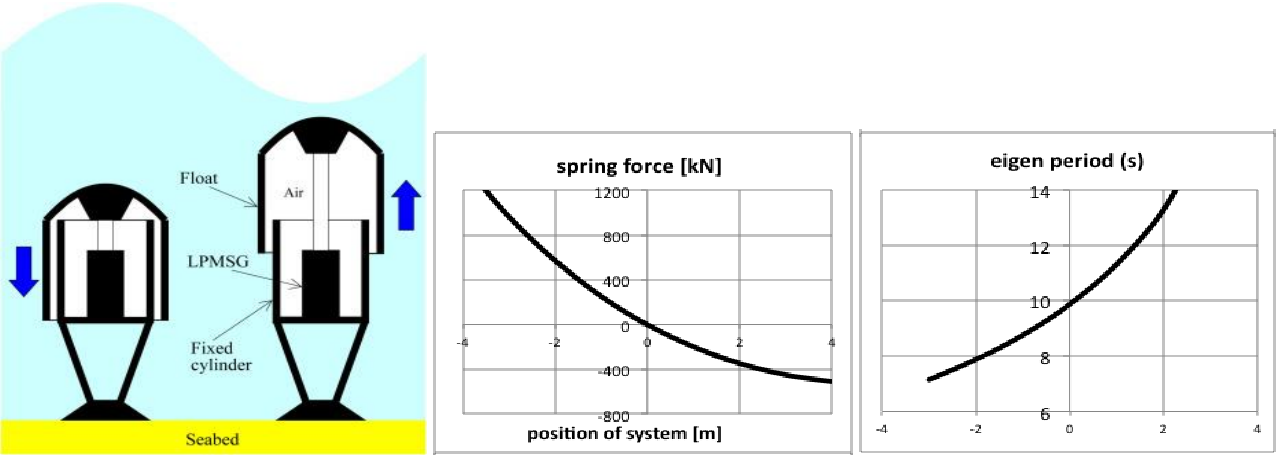


FIGURE 8: THE NON-LINEAR SPRING CHARACTERISTICS OF THE ARCHIMEDES WAVE SWING

More recently, CorPower introduced a resonant buoy as presented in (Figure 9), using an additional internal mechanical negative spring for actively adjusting the total spring force to the desired range.

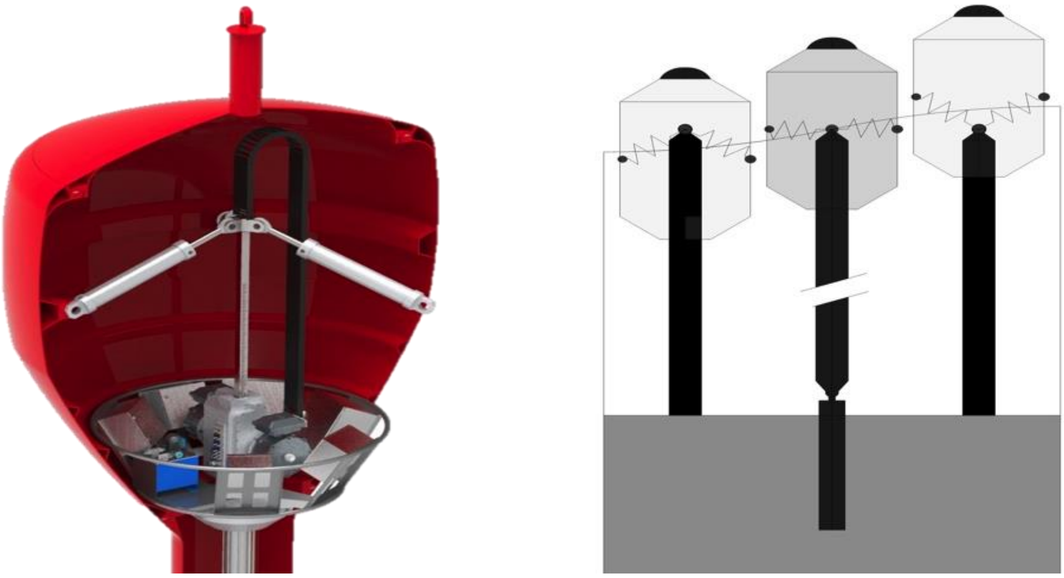


FIGURE 9: CORPOWER OCEAN AB (IMAGE COPYRIGHT CORPOWER OCEAN AB) INCLUDES AN INTERNAL NEGATIVE SPRING TO BECOME RESONANT.

Inside the system a negative spring is connected between the hull and the reaction leg. The negative spring in this case is composed of two pre-tensioned springs aligned in the same horizontal axe. The springs produce zero force with the system in mid-position and maximum in its end positions pointing away from its equilibrium. This spring is defined as a negative spring, and a good and tangible example of its putting into practice as a mechanical system. The spring can weaken the stiff spring from the buoyancy to a level that the device becomes resonant to the wave for wave devices that resonate at higher frequencies than those of the

incoming ocean waves. The developers expect efficiency improvements up-to 300% compared to an untuned device.

As mentioned beforehand, resonance can be achieved by increasing mass as well. The spar buoy concept (Figure 11, Section 2.3) is a good example of having a surface to act on by the wave pressure near to the surface. By adding mass, resonance is displaced to higher periods and so this is a possible way to match the incoming wave periods. The trade-off is however a more narrow-band operation, as well as a potentially high mass-to-power ratio and higher mooring forces. The Spar OWC and possibilities to introduce negative spring into OWC systems in general has been subject of Deliverables 2.1 and 2.3 of the WETFEET project [1, 3]. Some of the findings of these Deliverables are summarized in the following, as support to discussing the specific case of OWC, with respect to a potential implementation of the Symphony membrane as negative spring.

2.2. Implementation of the negative spring in WECs

The membrane with an air tank as a negative spring can be used in heaving wave energy devices, submerged or floating. In the image below several options for implementing the negative spring in different WEC's are presented.

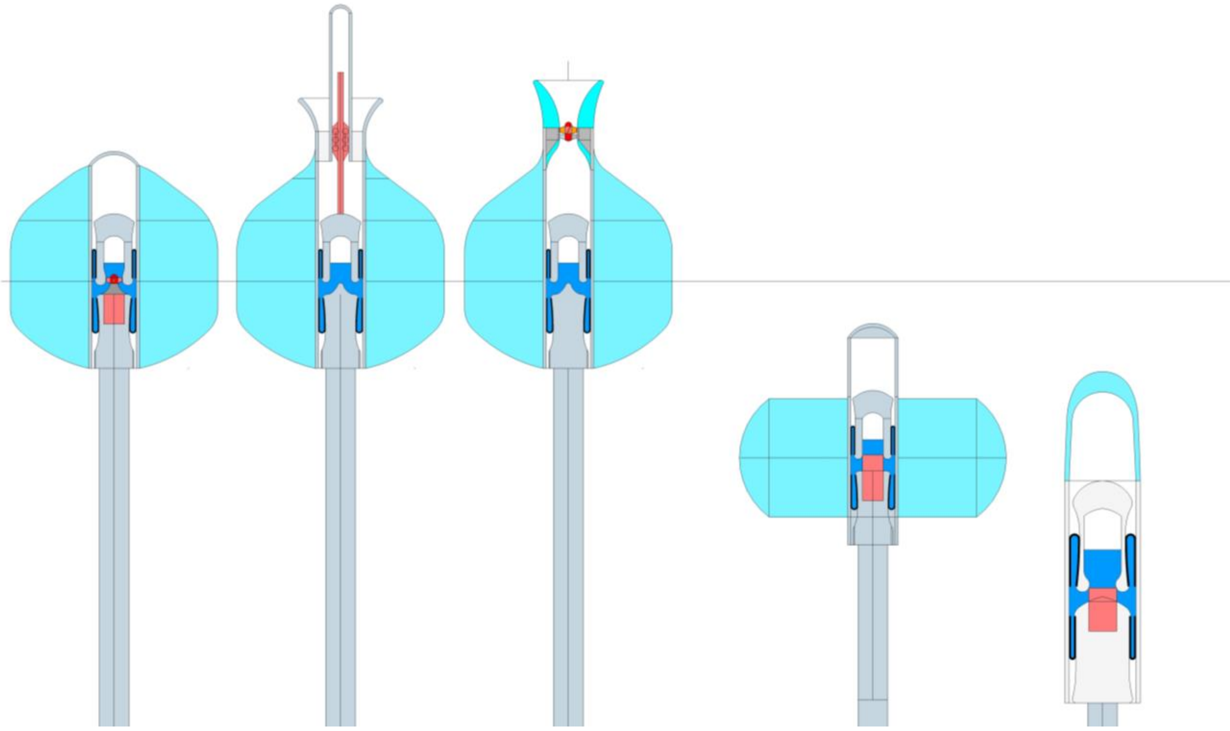


FIGURE 10: MEMBRANE AND AIR TANK AS INTERNAL NEGATIVE SPRING APPLICATION FOR DIFFERENT TYPES OF FLOATING WECS AND DIFFERENT PTOS

From left to right:

1. Floating point absorber with internal water turbine

In this option the negative spring is placed upside down in comparison to the Symphony application because it has to opposite the hydrostatic (positive) spring, as in any floating device. In this case the PTO is a water turbine.

2. Floating point absorber with a cascade PTO drive

In this option the negative spring is placed upside down in comparison to the Symphony for the same reason as in case 1. In this setup a cascade drive is considered, but it could be replaced by a linear generator or a hydraulic ram. An additional advantage of the membrane is that it also functions as a guiding system for the horizontal force acting on the buoy.

3. Floating point absorber with air turbine

In this option the negative spring is placed upside down in comparison to the Symphony application for the same reason of case 1: it is a floating device. The PTO is a air turbine. The volume displacement is dependent on the size of the membrane and may require a design a bit different for OWC open to the atmosphere as it may lead to higher pressure drops and smaller flow rates.

4. Fully submerged point absorber

In this application the negative spring is placed in a submerged buoy. These type of buoys are often buoyant, so the negative spring is placed upside down in comparison to the Symphony application.

5. Volume changing submerged point absorber

In this case the membrane is placed inside a volume changing point absorber. The spring functions as a positive spring, compensating the negative spring of the water pushing the hull of the device down. Together they result in a weak positive spring.

Using a membrane and a spring tank as in Figure 10 allows the PTO to be in a controlled environment but limits the volume displacement to the size of the membrane. This acts as negative spring, end stop and bearing system. PTOs like air turbines benefit from the large volume displacements of OWC's. Therefore a different approach is desirable for OWC's. In the next paragraph, the approach of implementing the membrane with air tank as internal negative spring is explained.

2.3. Specific considerations for implementing the membrane in an OWC

Within the ongoing project efforts of the WETFEET project, both an OWC spar buoy and a Symphony WEC have been analyzed in parallel, with respect to potential 'breakthrough' components (see [1-3]). Both device types represent promising classes of devices (OWC and submerged pressure differential point absorbers), and can serve as a starting point for assessing potential 'breakthrough' components for similar devices. The OWC spar buoy can be considered as a heaving point absorber WEC because:

- ✓ The two horizontal dimensions (i.e. length and diameter) are very small compared to a typical wave length of fully-developed seas.
- ✓ The body structure and internal free surface of the water column are primarily moving in heave.

The OWC spar operates from the relative heaving motion between the internal water free surface and buoy structure. One should aim to bring the heaving point absorber in resonance with the incoming waves. A spar buoy does this using a ballast, lowering its resonance frequency.

In Deliverables 2.1 and 2.3 of the WETFEET project (see [1,3]), the concept of a negative spring to optimize the power conversion capacity of OWCs is explored, and two specific methods to realize a negative spring in an OWC spar buoy are analyzed.

In order to enhance relative motion of the internal water column and the wave/air chamber of the OWC spar buoy, the draft of the Spar is designed quite large as depicted in Figure 11, resulting in a buoy with large dimensions and mass. In the following, two methods for the application of a hydrodynamic "negative spring" effect are recapitulated from former exploration within the WETFEET project. Both methods were conceived by WavEC Offshore Renewables, followed by a preliminary feasibility analysis (see [1,3]). In addition, WavEC has been conducting an in-depth analysis of a more promising idea.

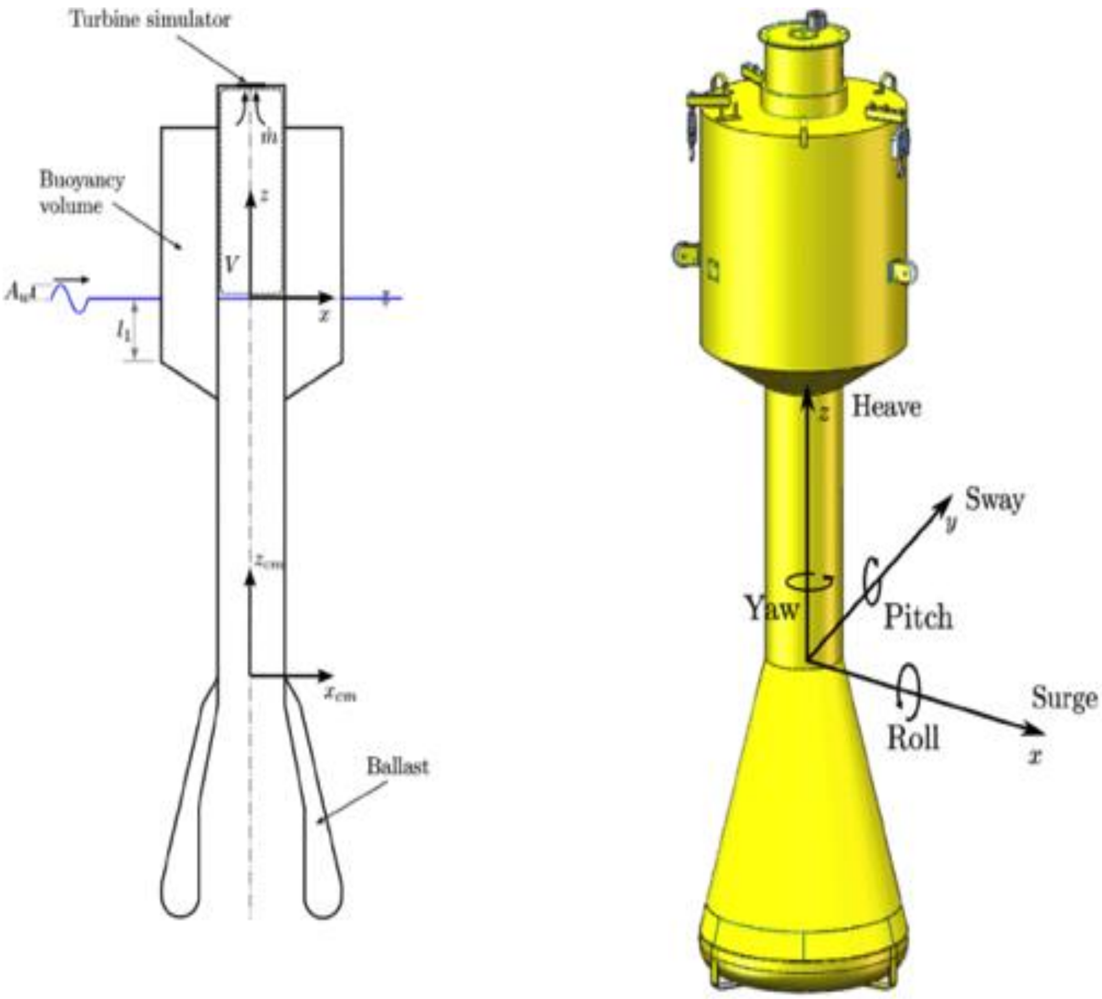


FIGURE 11: OWC SPAR BUOY OF THE TYPE THAT HAS BEEN ANALYSED WITHIN THE WETFEET PROJECT (DELIVERABLES 2.1 AND 2.3).

THE HNS NEGATIVE SPRING METHOD

An alternative method for achieving the negative spring effect in an OWC spar buoy is the so-called Hydrodynamic Negative Spring (HNS). The Floating OWC (FOWC) is analogous to a two-body oscillating Wave Energy Converter (WEC), in that the water column acts as a second body with its own resonant frequency. If the WEC's Inner Free Surface (IFS) diameter is significantly smaller than the wavelength of incoming waves, the second body may be modelled by a massless piston of infinitesimally small thickness placed on top of the water column.

The HNS method applied to the FOWC involves widening the tube inside the floater and filling this space with seawater on the downward cycle, which is then transferred back to the sea in the upward cycle. In doing so, the buoyancy is reduced on the downward cycle because less seawater is displaced, and increased on the upward cycle because more seawater is displaced.

By its nature, implementing the HNS method into a full-scale OWC spar buoy would not induce significant extra engineering challenges other than those inherently foreseen for the

reference OWC spar buoy design. Indeed, the HNS method only implies enlarging the IFS of the floater. The manufacturing and assembly procedure might become slightly more complicated and the structural integrity may also be weakened. Also, some additional viscous losses may exist and so further analysis employing non-linear modeling such as Computational Fluid Dynamics (CFD) and experimental testing should be done. In particular, the hydrodynamic behavior precisely where this widening of the internal diameter occurs should be studied. In turn, this would lead to the estimation of the loads experienced at this location and a structural analysis could inform what the revised specifications should be for fabrication of the unit.

PROPOSAL: THE INTERNAL NEGATIVE SPRING METHOD

In the OWC spar buoy (see Figure 11) the resonance of the oscillating water column is enabled by the large dimensions and ballast of the spar buoy structure. By using the membrane and spring chamber as an internal spring, the ballast can be removed from the OWC spar buoy. By this means, a regular OWC is created but still having the same benefit as the spar buoy. Similar and even larger air flows can be generated using this setup, which allows similar PTOs, like the novel tetra-radial air turbine developed under the WETFEET project (WP4). The mooring setup would require a fixed tension leg or monopole instead of semi free moving moorings or else a drag plate to stabilize the central cylindrical rod.

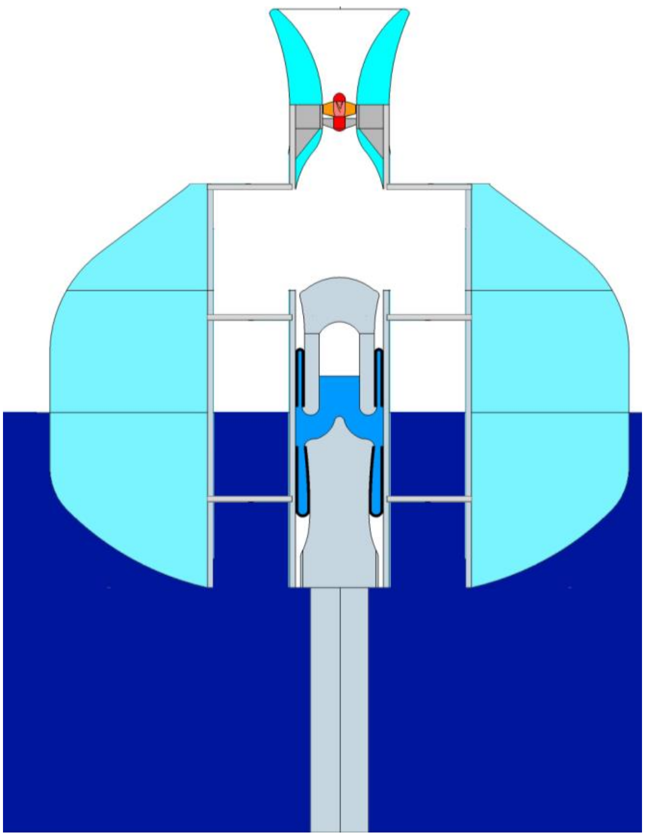


FIGURE 12: OWC WITH NEGATIVE SPRING PROVIDED BY SYMPHONY BELLOW FRAME AND MEMBRANE MODULE

3. Symphony membrane as negative spring for point absorbers buoys

Within the WETFEET project, critical components have been developed to bring wave energy closer to the market. These components should solve critical parts of existing technology. Within resonating point-absorbers, there are number of critical issues. One is, as discussed, an internal negative spring to reduce the natural frequency if these devices to make them resonate at the incoming wave frequencies. Other issues are however bearings, seals and end-stops. Especially end-stop technology is a major issue in resonating devices. As the tuned mass spring system is capable of charging itself, the motion will increase if the energy is not tapped from the system. In normal operation, the Power-take-off (PTO) system will absorb a significant part the wave power, as this is the goal of the whole system, thus limiting the motion amplitude of the device below design values. In some cases, however, the PTO might fail, or the amount of available wave power may exceed the PTO design power. In such a case the device motion amplitude will grow above the design value putting the device at risk, except if an alternative power dissipation mechanism is conceived (the end-stop mechanism). In the design strategy of a heaving type WEC, this is of major importance as the PTO is a costly item. If it has to be sized to the highest waves that rarely occur it will become a prohibitive cost factor and it will operate at very low efficiency in the very frequent low wave conditions. Therefore there is a need for a good end-stop, which can stop the motion in a convenient way, independent of the PTO and without too much extra cost.

The structural membrane solution proposed by Symphony is a construction combining a bearing, an end-stop and a special shaped negative spring function (see Figure 13, Figure 14 and Figure 15), which is in the focus of the considerations presented in this document.

3.1. Working principle of the Symphony membrane system

As the outer hull is displaced downwards (see Fig. 15), two bellow frames roll along the inner wall. The pressure inside is defined by the pressure in the compressed air space, and is significantly higher than the pressure level surrounding the device. The two bellow frames are therefore under over-pressure and the forces they apply on the outer wall in vertical direction, counteract each other. This resulting force is determined by the difference of the lower and upper membrane cross-section towards the outside.

The bellow frames bridge the space between the outer hull and the reference wall. By shaping this reference wall the designer can determine the characteristics of this unit, and introduce a wide range of desired force balance along the entire effective stroke length. For one system this can be a negative spring to weaken the hydrostatic spring of a buoy (in this case the top cross section of the upper bellow frame is smaller than the bottom cross section of the lower bellow frame). In the Symphony device itself it creates a spring to be resonant in the middle of its motion, while at the end of stoke it transfers into a stiff spring that acts as an end stop. This end stop feature can also be attained in other point absorbers.

Figure 13 shows a functional sketch of the membrane system and its main components, and Figure 14 shows the relative position of external (moving) and internal (reference) body on both ends of stroke. Figure 15 illustrates how the membrane system is integrated into the device (in this case in combination with a water turbine as PTO). As previously mentioned, in this setup the membrane system operates as a positive spring.

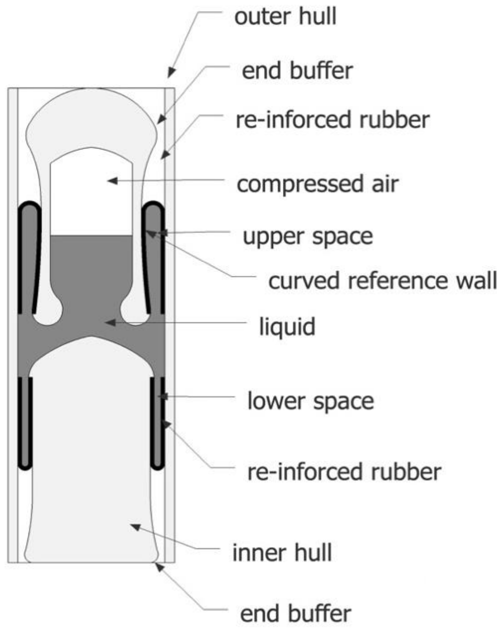


FIGURE 13: THE INNER CORE OF THE SYMPHONY SYSTEM AND ITS MAIN COMPONENTS

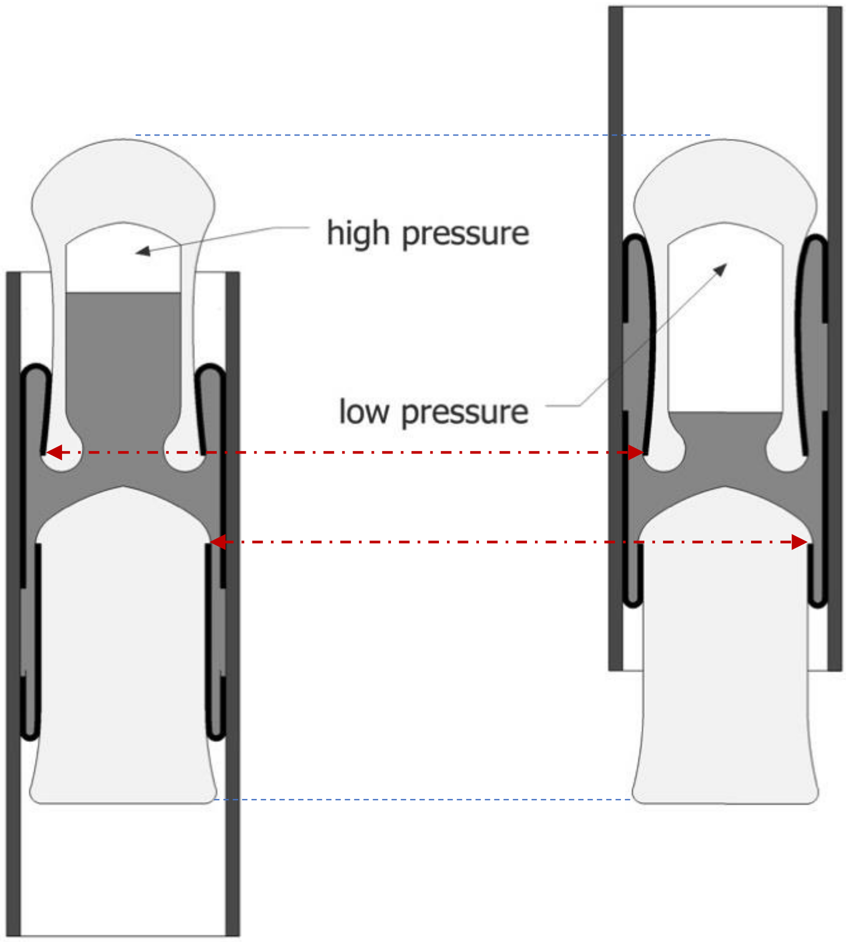
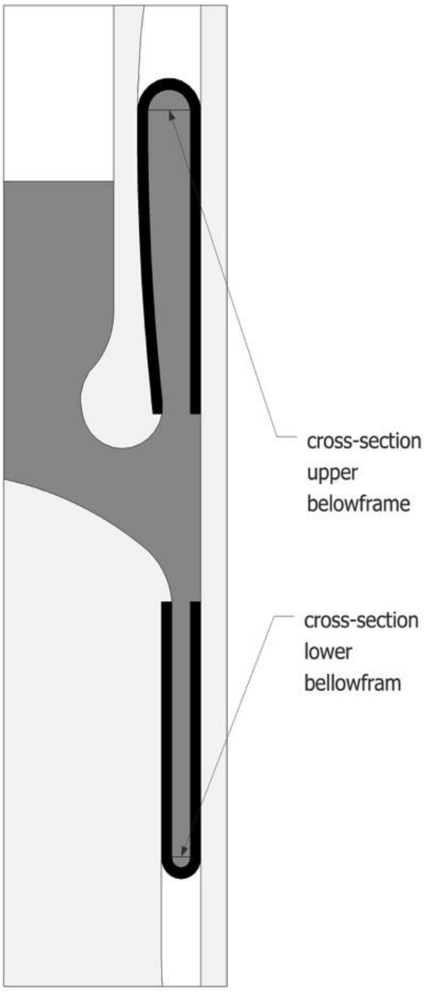


FIGURE 14: STATUS OF SYMPHONY MEMBRANE COMPONENTS IN LOWER AND UPPER POSITION



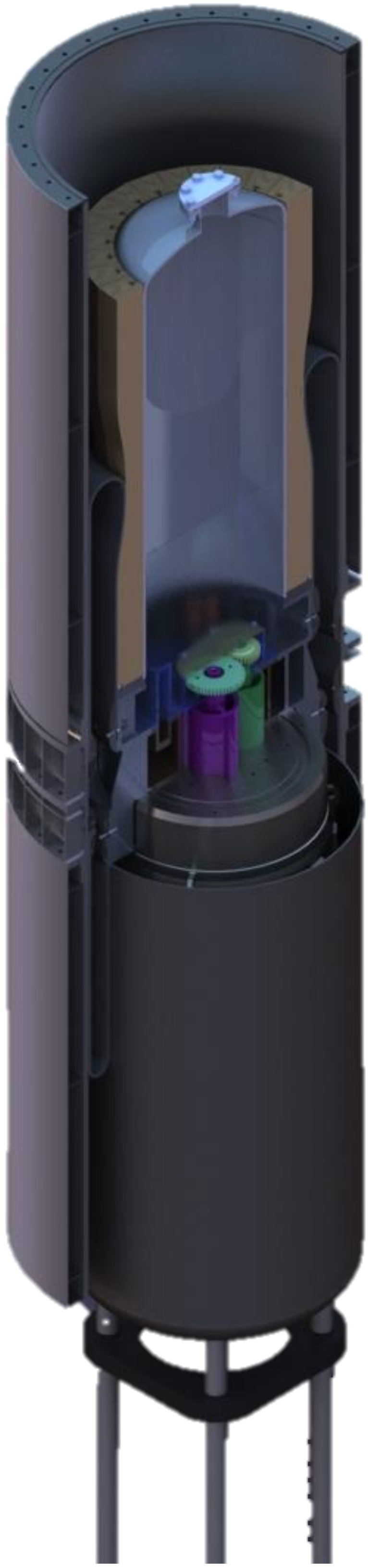


FIGURE 15: VARIABLE CROSS SECTION BELOW FRAME (LEFT); ARTIST'S IMPRESSION OF THE INTERIOR OF THE SYMPHONY PTO MODULE COMBINING A BEARING, SPRING, END STOP AND WATER TURBINE

In Figure 16, an example of the characteristics is given for a 6 m diameter Symphony, when the above presented system is implemented and tuned to the desired forces (by modification of inner wall geometry of the bellow frame). The stiff spring at the end of the stroke is able to restrict the motion at the highest wave in the highest operational sea state. Being a spring, the energy in the end stop is not dissipated, but given back to the motion. Therefore, for acting on high waves at the end of stroke, the spring is stiff, the system is de-tuned for the next wave and energy is lost in the radiated wave and turbulence.

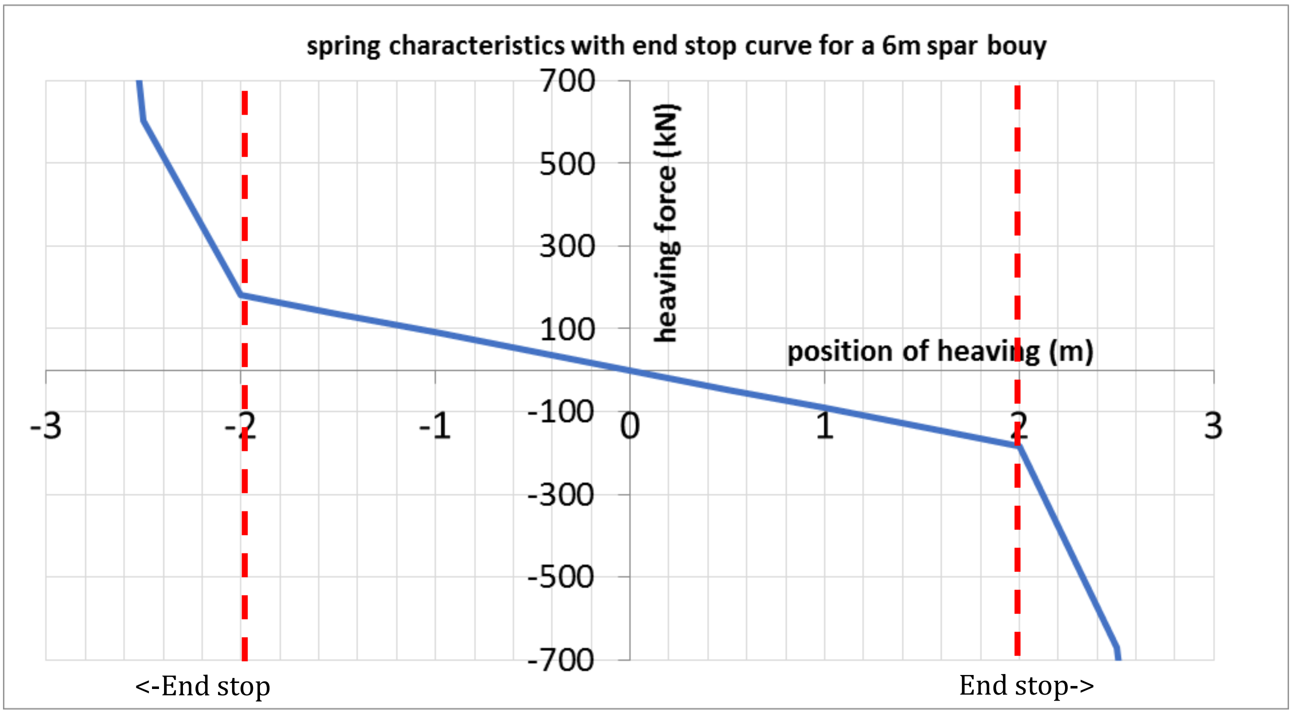


FIGURE 16: SPRING CHARACTERISTICS WITH END STOP CURVE.

The Symphony is a system like the Archimedes Wave Swing, being submerged, with the outer hull moving along the central part. The difference is that the interior is formed around the “Symphony spring unit” with a double below frame. As described above, the characteristics of the spring, bearing and end stops are well defined within this unit.

In order to find the optimal shape of the braking force, an analysis was performed, taking into account practical aspects of the operation. As the device is connected to the seabed with a tensioned anchor line, too much braking force will cause the line to go slack. Also too much upward force might lift the gravity based anchor from the seabed. These limits are given by the dashed red lines in Figure 16.

As mentioned above, a similar setup, with or without the water turbine (if the selected WEC PTO is of a different type), can be designed to operate as a negative spring (in which case the Symphony membrane is mounted upside-down) with the appropriate spring stiffness and installed in different types of point absorbers, as will be seen in the next section.

3.2. Performance and conceptual design for membrane implementation into other heaving WECs

In Figure 17 a sketch is given of the working principle of such an integration. This design gives high output due to resonance, while the PTO unit can stay at 1/3 of the diameter of the buoy. It should be noted that this is one of different possibilities to integrate the Symphony membrane system into a heaving point absorber buoy. Here, a Symphony water turbine is sketched as PTO, while in a similar manner there could also be the membrane system in combination with an existing/preferred linear PTO, e.g. rack & pin, linear generator, spindle drive, hydraulic rod, etc..

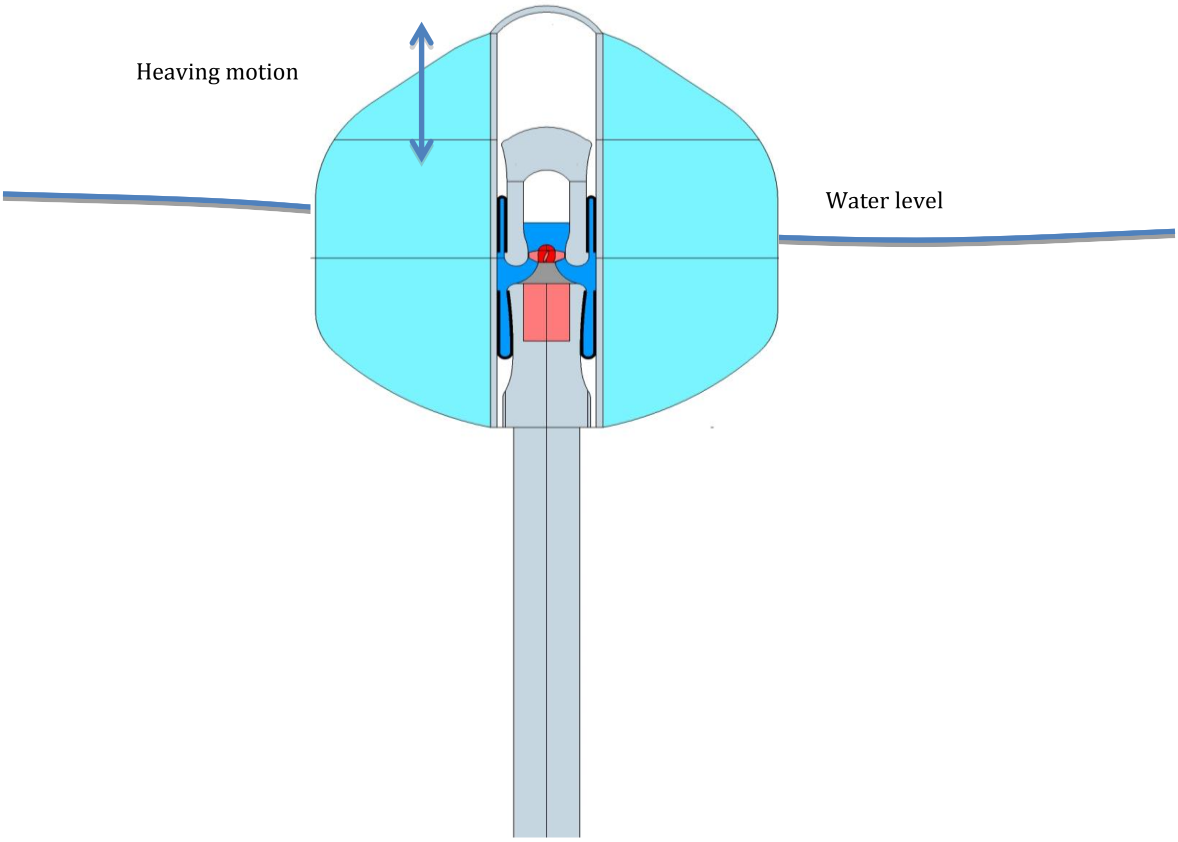


FIGURE 17: SYMPHONY BELLOW FRAME INTEGRATED IN A SURFACE PIERCING BUOY TO GIVE IT A NATURAL FREQUENCY CLOSE TO THE FREQUENCY OF OCEAN WAVES. INDEED THE SYMPHONY BELLOW FRAME CAN BE DESIGN TO MATCH ANY WAVE FREQUENCY (WITHIN LIMITS).

To illustrate the potential of the membrane system to be incorporated in other heaving WECs, the following example shows the PTO unit integrated in a floating buoy (type "a", Fig. 5). By shaping the walls of the bellow-frames appropriately, the spring characteristics will add a

negative spring to a too stiff positive hydrostatic spring. As a result the spring characteristics shown in Figure 18 are obtained.

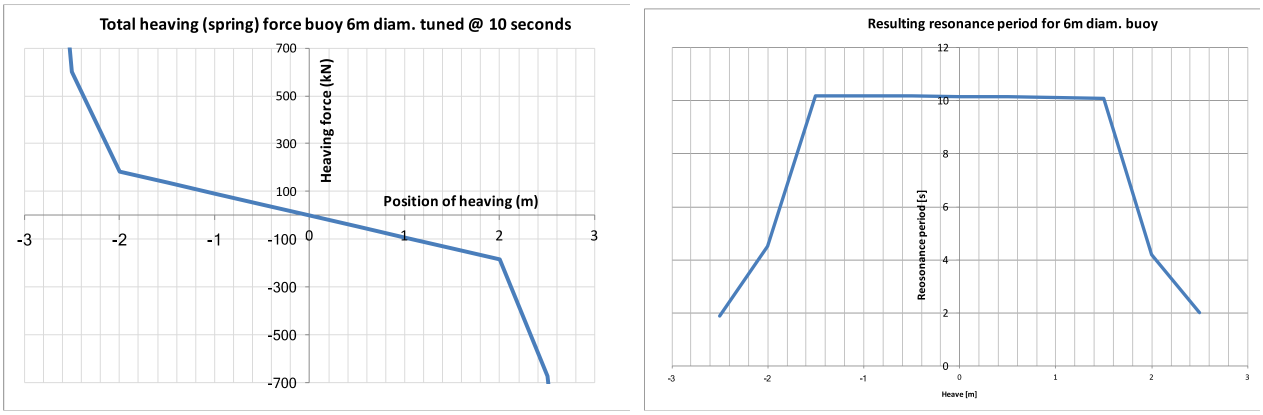


FIGURE 18: RESULTING SPRING CHARACTERISTICS OF A 6M DIAMETER SURFACE PIERCING BUOY WITH SYMPHONY BELLOW FRAME.

The following Table 2, Figure 19 and Figure 20 show a more detailed view on how the relevant components of the spring force sum up, as well as other dimensions involved. This exemplary calculation has been done for the buoy diameter of 6m. The resulting spring force presented in Figure 18 is displayed together with their main components, and more illustrative along its vertical stroke in Figure 20.

TABLE 2: DETAILED CALCULATION STEPS FOR MEMBRANE-INDUCED SPRING AND TOTAL SPRING FORCE OF A 6M DIAMETER BUOY WITH THE SYMPHONY MEMBRANE.

			buffer low			operational stroke							buffer high		
position of the seal from low to high	m		-1.5	-1.25	-1	-0.75	-0.5	-0.25	0	0.25	0.5	0.75	1	1.25	1.5
diameter outside	m		1.875	1.875	1.875	1.875	1.875	1.875	1.875	1.875	1.875	1.875	1.875	1.875	1.875
Seal 1															
top seal															
diam inside	m		1.4375	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.625	1.75
surface seal	m2		1.14	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.69	0.36
V	m3		-1.71	-1.24	-0.99	-0.75	-0.50	-0.25	0.00	0.25	0.50	0.75	0.99	0.86	0.53
Seal 2															
bottom seal															
diam inside	m		1.750	1.563	1.513	1.527	1.542	1.556	1.571	1.586	1.602	1.619	1.636	1.688	1.556
surface seal	m2		0.36	0.84	0.96	0.93	0.89	0.86	0.82	0.79	0.75	0.70	0.66	0.52	0.86
V	m3		-0.53	-1.05	-0.96	-0.70	-0.45	-0.21	0.00	0.20	0.37	0.53	0.66	0.66	1.29
difference between two seals															
d A	m2		0.78	0.15	0.03	0.06	0.10	0.13	0.17	0.21	0.25	0.29	0.34	0.16	-0.50
volume	m3	6	6	6	6	6	6	6	6	6	6	6	6	6	6
change of volume	m3		-1.17	-0.19	-0.03	-0.05	-0.05	-0.03	0.00	0.05	0.12	0.22	0.34	0.20	-0.75
Volume for pressure	m3		4.827	5.812	5.970	5.952	5.950	5.966	6.000	6.052	6.124	6.218	6.336	6.203	5.245
pressure	kN/m2		3119	2405	2316	2326	2327	2318	2300	2272	2235	2188	2131	2195	2776
force	kN		2440	362	68	150	231	312	393	474	555	636	716	357	-1397
spring	kN/m			2372	212	-163	-163	-162	-162	-162	-161	-161	279	2113	
Buoy position			-3	-2.5	-2	-1.5	-1	-0.5	0	0.5	1	1.5	2	2.5	3
dia	m	6	6	6	6	6	6	6	6	6	6	6	6	6	6
working surface	m2		25.51	25.51	25.51	25.51	25.51	25.51	25.51	25.51	25.51	25.51	25.51	25.51	25.51
rho	kg/m2	1015													
draft		4	7	6.5	6	5.5	5	4.5	4	3.5	3	2.5	2	1.5	1
displacement	kN		1776	1650	1523	1396	1269	1142	1015	888	761	634	508	381	254
spring	kN/m			254	254	254	254	254	253.8	254	254	254	254	254	
						RESULTING TOTAL FORCES									
			lower buffer			Middle area							upper buffer		
position	m		-3	-2.5	-2	-1.5	-1	-0.5	0	0.5	1	1.5	2	2.5	3
total spring	kN/m			2626	465.8	91.19	91.23	91.37	91.59	91.89	92.28	92.76	532.6	2367	
Mass floater inc ballast	Ton	59	-1409	-1409	-1409	-1409	-1409	-1409	-1409	-1409	-1409	-1409	-1409	-1409	-1409
total static restoring force	kN		2808	602	182	136	91	45	0	-47	-92	-139	-185	-671	-2552
dinamic mass (factor 1.7)	Ton	101													
resonance period	sec			1.90	4.50	10.18	10.18	10.17	10.16	10.14	10.12	10.09	4.21	2.00	

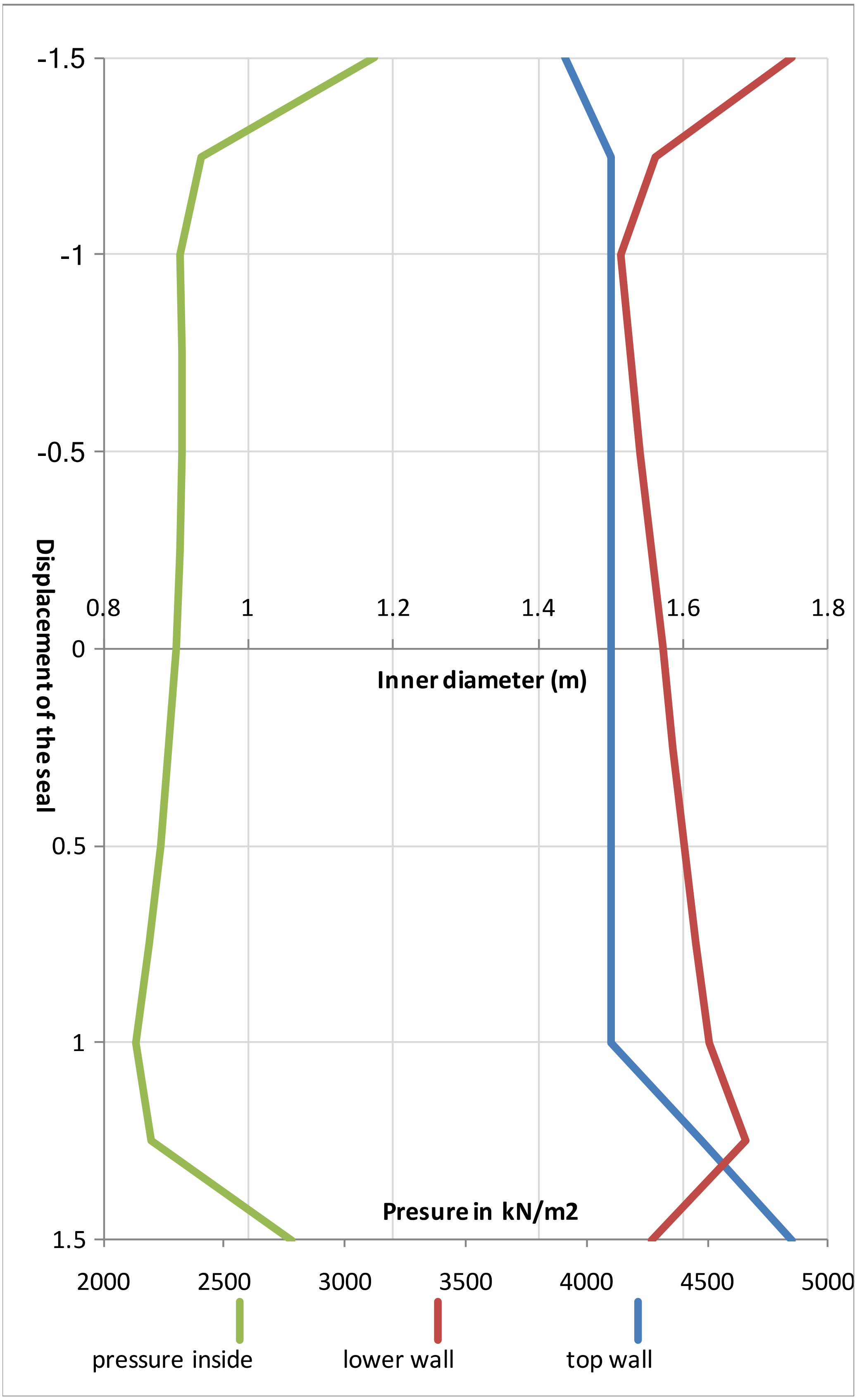


FIGURE 19: REPRESENTATION OF INNER WALL GEOMETRY FOR UPPER AND LOWER WALL, AND INSIDE PRESSURE VARIATION ALONG OPERATIONAL STROKE, FOR A 6M BUOY.

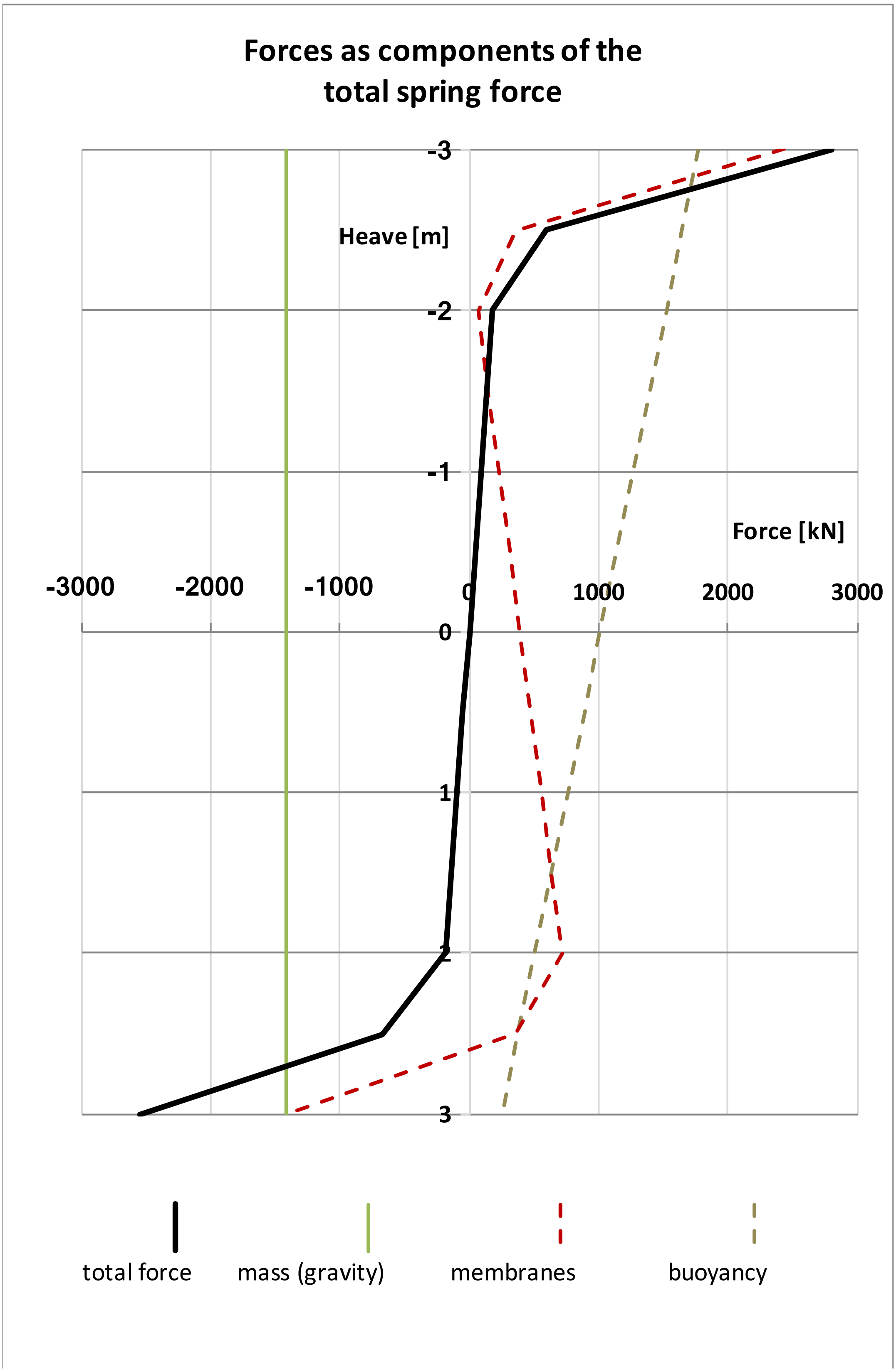


FIGURE 20: DETAILED REPRESENTATION OF FORCE COMPONENTS ALONG THE OPERATIONAL STROKE.

3.3. Feasibility of membrane for large-scale applications

In practical terms, all types of heaving point absorbers could be equipped with a Symphony membrane system with characteristics in the range of what is discussed in section 3.2, presuming that the membrane system itself proves feasible in e.g. a Symphony prototype. The issues for large-scale implementation of Symphony systems in general are discussed in Deliverable 2.3 of the WETFEET project [3]. To judge whether or not the membrane would represent an improvement of overall performance and/or cost-benefit ratio, strongly depends on the 'conventional' solution it is compared to. As opposed to Submerged Pressure Differential WECs like the Archimedes Wave Swing or Symphony itself, for heaving point absorbers other technical solutions than the membrane are being developed and tested elsewhere. Typically PTO and end stop system are separate components whereas the Symphony membrane unites both these functions in a theoretically fail-safe manner. Provided that this function shows in practice the predicted characteristics, there are no specific limitations to apply the Symphony membrane to other WECs, providing the required negative spring and end stop functions as demonstrated in section 3.2.

In the following, some aspects comparing large-scale implementation of Symphony membrane systems versus existing solutions for other WEC types are discussed, knowing that this is a rather conceptual exercise due to the relatively early stage of development and lack of proven and published operational data for either of the solutions.

3.3.1. Generic heaving WECs

For the reference case of 6m diameter heaving buoys, the bellow frame for the Symphony membrane system will require a minimum shaft diameter of approx. 2m over the entire stroke length plus the end stop zone (e.g. 0.5m on each upper and lower end), in order to house the components. Apart from this, no specific requirements exist to integrate the Symphony in a heaving WEC.

TABLE 3: COMPARATIVE CONSIDERATIONS OF SYMPHONY MEMBRANE SYSTEM VERSUS EXISTING SOLUTIONS FOR HEAVING POINT ABSORBERS.

WEC geometry and negative spring	Typically, a heaving point absorber consists of a specially shaped buoy connected by a cylinder leg to a damping plate in some depth or else to the sea bottom by a pretension mooring line. In case no dedicated internal spring exists but resonance is achieved mainly by a larger diameter buoy or by a submerged mass, the implementation of an internal negative spring is likely to bring significant improvements (smaller WEC geometry / less mass for same hydraulic performance, or increased hydraulic performance for same geometry).

	Existing alternatives for internal spring systems would be mechanical, actuators either with pneumatics or hydraulics. In terms of spring functionality and space requirements and potential impact on WEC geometry, a priori both alternatives can be expected to have comparable performance (e.g. CorPower).
End stops	End stops may represent the biggest challenge for heaving point absorbers. Not only in extreme seas, but also – and in particular – in highly energetic operational wave conditions with high resonance effect, the risk of damaging or destructive bumping of two mowing bodies against each other in the end of stroke zone is high for conventional systems (usually mechanical). There has not been published or otherwise made credible a functioning and fail-safe end stop for heaving point absorbers, which makes the Symphony membrane with its intrinsic de-tuning and ´soft´ end stop (without mechanical impacts) a potential candidate to substantially improve large-scale implementation scenarios.
PTO	For linear PTOs (e.g. rack & pin, linear generator, spindle drive, hydraulic rod, etc.), the most critical aspect is probably the sideway tolerances and bearing forces between the two bodies moving against each other. The membrane has been analysed regarding this aspect and its function as bearing/centring force is introduced in Deliverable 2.2 [2], and further discussed in Deliverable 2.3 [3]. The required internal air/water pressure of the Symphony bellow frame and the consequently exerted centring force on the membranes needs to ensure that sideway movements an forces encountered by the bearings of linear PTO remain within the tolerances. For a floating device with a certain PTO, this requires specific analysis. Especially the hydrodynamic side forces on the buoy might be higher and/or more unpredictable for floating point absorbers. In the particular case of the Symphony bellow frame combined with a water turbine PTO (as investigated in WP4 of the WETFEET project), the system provides spring, bearing, end-stops and PTO in one adequately tuned and synchronised module, with no mechanical risks. The typical bearing issues known for linear PTO could thus be eliminated. However, the water turbine needs to be tested in physical environment before statements about its performance and suitability for wave energy can be established. This is part of WP4.
O&M issues	The reliability, fatigue issues and cost of one or more actuators and the pneumatic/hydraulic circuit for the desired force range has to be weighed against a Symphony bellow frame. In theory, the latter is more resilient and involves less delicate or complex parts. Main operational risks will be potential leaks of the pressurised air-water volume, potential failures of pressure adjustment circuit, and operation life cycle

	of membrane (and connections). All of the latter may be disregarded as potential risks once the Symphony system is demonstrated in real-scale environment.
Overall cost	Membrane material and attachment costs would be the most relevant cost item for the Symphony, and they are being further analysed in the ongoing WETFEET project. The main materials are rubber and synthetic fibres, both having reasonably low and stable raw material costs. In the beginning, it is mainly the non-standard manufacture and installation process, as well as the limitation of dimensions of existing manufacturing capacities for the membrane that are an obstacle for economic feasibility. Once the level of serial production is reached, there is no obvious obstacle for the Symphony bellow frame turning more cost-efficient than other combinations of PTO and end stops. This applies in particular to a combination of the Symphony membrane and water turbine.
Other	At conceptual level, and after the indications that the WETFEET project has so far resulted in with respect to the membrane and the turbine, especially the combination of both, but also only the bellow-frame as spring and end stop, combined with a linear PTO, appear to be feasible options for large-scale heaving point absorbers. A more detailed estimate of force levels and spring requirements, as well as lateral forces between the floater and the reference structure need to be done before a final conclusion can be drawn on the use of the Symphony membrane in other point absorbers. These will require detailed hydrodynamic analysis, and an integrated time domain model for the next step of analysis.

3.3.2. OWC

As previously mentioned, an OWC with a Symphony bellow frame could be considered a specific case of a "2-body" heaving point absorber, with variable air volume between (upper) floating body and (lower) reference structure. Assuming similar dimensions, and that the relative body movement will be in the same range like a generic heaving point absorber, the stroke will be equally limited by the membrane system, and forces and mechanically available power levels can be expected to be comparable. Yet when discussing the feasibility of such a "Symphony OWC" to existing solutions, some aspects vary with respect to the generic heaving point absorber.

TABLE 4: COMPARATIVE CONSIDERATIONS OF SYMPHONY MEMBRANE SYSTEM VERSUS EXISTING SOLUTIONS FOR OWCS.

WEC geometry and negative	As a floating OWC does normally only have the air volume and the change in buoyancy acting as spring, there are not many other options to

spring	actively adjust the spring by geometry changes, as discussed beforehand (see section 2.3). This will result in rather large dimensions or the use of an underwater mass, and consequently increased material and (especially) installation costs. Larger marine means will have to be mobilised, and mooring forces will be higher. On the other hand, the implementation of a Symphony bellow frame as a negative spring and turning the otherwise "one-body" structure of an OWC into a 2-body heaving WEC, introduces an added grade of complexity and structural vulnerability. Especially along the total stroke area, dynamic forces and bearing tolerances will play a role, structural reinforcements in this area will be required. However, as functional mode, PTO and varying volume air chamber are identical to an OWC, such a device would benefit from the wide R&D and operational experience that already exists for OWCs. Its development and implementation could be done in parallel, and implemented once OWCs and air turbines reach higher grade of maturity. The reference structure with the mooring point, air tunnel, Symphony module and air inlets is an new type of structural unit, which however could be built from a cylindrical barebone, facilitating the options for strength and manufacturing methods.
End stops	Given that a conventional 1-body OWC does not require end stops, the implementation of Symphony membrane introduces an added grade of complexity. In a regular OWC no large structural parts moving against each other, which makes it one of its major arguments for large-scale application due to its simplicity and potentially less structural/mooring risks. The Symphony bellow frame on the other hand, is designed to act as 'soft' end stop, meaning there will be no mechanical impacts. Demonstration of the Symphony membrane system as feasible and reliable end stop is required to approach these issues in more detail.
PTO	For the PTO of an OWC, which is usually an air turbine, there are no specific benefits or drawbacks expected when using the Symphony module as negative spring. There might be some additional spray caused by the structural reinforcement required to cross the inside of the air chamber, but it is questionable to which point this is significant. By this means, turbine stall events could be significantly reduced, as these occur due to faster changing air volumes than what can be handled by the turbine. To date, it has been one of the most significant challenges for efficiency and maintenance of air turbines, something that is expected to be to a great extent controlled by the new tetra-radial turbine (see Deliverables 4.1 and 4.4).
O&M issues	The aforementioned stall events negatively impact turbine blades, bearings and stator blades, if existing. In addition to likely having a

	positive influence on this aspect, the implementation of a Symphony membrane system would increase the accessibility of the air chamber and turbine, due to the possibility of de-tuning or even locking the motion when access is desired.
Overall cost	At this stage of development, it is not credible to make comparative cost statements between other methods and the Symphony membrane system as negative spring. For capital cost, the increased material, construction and in particular handling/installation costs for a large Spar OWC would have to be weighted against the costs for a Symphony bellow frame system and the additional sealing/bearing between the moving bodies. Both have significant limitations in an early development phase: the large structure (in diameter and length) may induce limitations for available assembly places and may require costly installation vessels if cheap installation methods are not developed, and the membrane is a non-standard item (see generic point absorbers).
Other	The evaluation of the Symphony bellow frame / membrane system for integration in an OWC is a somewhat hypothetical exercise, as the combination has not yet been proposed by developer teams. It appears like a worthwhile alternative to conventional or Spar OWCs, and in particular to generic heaving point absorbers, as it combines some advantages of these. Further analysis however depends on successful demonstration of the Symphony membrane module.

4. Conclusions

The Symphony unit creates an ability for heaving point absorbers to become resonant to the waves, without increasing mass. This increases energy capture efficiency over a larger bandwidth. While originally developed within the EC-funded H2020 project WETFEET for a new generation of submerged pressure differential devices, the Symphony unit consisting of a structural membrane could also be beneficial for other heaving type WECs, including OWC. In case of heaving point absorber devices with linear PTO, optionally a water turbine PTO (developed in WP4 of WETFEET) could be integrated into the system, adding advantages with respect to survivability, O&M and cost issues (the latter will require physical demonstration of the integrated Symphony bellow frame membrane and turbine).

In this document, the existing options for providing a negative spring component, or more precisely, a spring component fully adapted to the needs of heaving WECs are discussed, and compared to a corresponding WEC with the Symphony bellow frame providing the spring, end stop and (main) bearing. Further the vision of a modified OWC is presented and discussed, in which the negative spring is provided by a Symphony module, thus potentially saving costs by replacing the spar buoy ballast, and enabling significantly smaller dimensions.

Although the conceptual exercise builds on a number of assumptions that have to be confirmed by physical testing and prototype operation, the outlook for the integration of the Symphony core unit into other WECs, and thus providing a potential solution for key challenges of point absorbers spanning different technologies, is promising.

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