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Deliverable 3.5 Engineering of Symphony critical parts related to continuous submergence for large scale deployment

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0	20 April 2017 - Deliverable structure defined
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WETFEET

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EXECUTIVE SUMMARY

This report presents Deliverable 3.5 of the WETFEET H2020 project – Report with engineering of Symphony critical parts related to continuous submergence for large scale deployment. The critical components of the Symphony wave energy converter are housed in a separate, isolated compartment that is removable from the WEC, the control cocoon. This report contains the technical approach to the cocoon implementation and explains the engineering choices made for the critical items.

The key aspect for continuous submergence is the accessibility of vital components of the device for maintenance, or a simple and straight-forward system for the temporary removal of these. The approach taken in the original Symphony design is to gather all functional components that may require maintenance inside one encapsulated volume, which can be removed and re-placed into the device with moderate means, and under higher sea states than surface operations would allow. To assess the technical feasibility and – in a following stage - economic effect of this O&M strategy, an initial study of functional requirements, engineering constraints and potential configuration inside the cocoon is made, having in account existing technology, as well as in-house design.

This Deliverable summarises the activities in WP 3 related to assess design and functionality of a permanently submerged control cocoon as O&M strategy for the Symphony device by design of control cocoon hull (including numerical modelling), interfaces, sealing and bearings, tank testing including removal strategy; scale model manufacture of Symphony device with control cocoon and wave tank testing of scale model.

List of Acronyms

AWS	Archimedes Wave Swing
PTO	Power Take-Off
WEC	Wave Energy Converter
WP	Work Package

FIGURE 1: EXTERNAL VIEW OF THE CONCEPTUAL DESIGN FOR THE CONTROL COCOON, WITH MAIN COCOON STRUCTURE AND GUIDE WHEELS (BELOW), AND TRANSITION PIECE AND TURBINE (ABOVE)

1. INTRODUCTION

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. One of the breakthroughs that has been identified for the Symphony device is the continuous submergence, and the removal of critical components from the device without dismounting the complete wave energy converter. As a submerged floating structure, the Symphony concept has a potential edge over surface-floating devices, since it is less exposed to extreme loading under storm conditions and to brisk movements in operating conditions. However, the continuous submergence of a wave energy device naturally implies a fail-safe philosophy of sealing elements, as well as a new approach to access. The control cocoon containing the vital parts of the PTO and communication systems is the key to this approach.

Although access issues have been referred to as the major obstacle for fully submerged devices in the past, the operational reality may be slightly different: even for offshore wind turbines in relatively sheltered areas and equally for recent wave energy prototypes, the personnel transfer from a vessel to the device has shown to be relatively complex with some degree of risk including collision between the service vessel and the device. Especially for floating WECs, the personnel transfer involves two independently moving bodies, increasing the risk of sudden jerking movements and narrowing down the potential maintenance windows to a minimum. On the other hand, below the water surface, movements are much smaller, more predictable and smoother, the deeper the reference point. For a submerged device like Symphony, especially in the utility-scale commercial development phase, a fully submerged maintenance strategy by removal of key components can bring along significant advantages.

The control cocoon is the 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 lessons 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 [1]. Whereas in this specific project the developers managed to implement an ad-hoc modification of the test programme to bridge the most relevant gaps, in general such a scenario is very serious. The loss of controls or mal-functioning of components in operation typically requires the removal of the WEC for maintenance on land.

In the following, the technical approach to the implementation of this strategy using a removable control cocoon is presented, as well as conceptual engineering considerations for its realisation. The reference design for a 6m diameter Symphony is used as baseline, according to Deliverable 2.3 of the WETFEET project [2].

2. CONTROL COCOON DESIGN FEATURES

2.1. Control cocoon functional description

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 (see Deliverable 2.3 of WETFEET, [2]):

- **Turbine**: a custom dual direction turbine will be used to drive the shaft 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. The development of a purpose-designed turbine is dealt with in WP4. Relevant design specifications are included in Annex V, and initial design steps are reported in deliverable 2.3 [2].
- **Generator**: the shaft of the turbine is connected to a permanent magnet generator, which could be used to drive the turbine shaft, too. It is sealed in the interior of the cocoon and has no critical interfaces to the outside. The generator will be an off-the-shelf model, and an exemplary model is presented in section 2.2.6 and Annex VII.
- **Electronics and control system**: the electronics will be placed in a sealed box, from which the generator and valves of the pressure systems are controlled (and the winch, in case it is inside the cocoon). 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). The seals are discussed in section 2.2.3 and potential models included in Appendix V.
- **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 bar. 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. The spring adjustment tank is not part of the design steps in this phase, as it is considered an uncritical item, which can be adjusted and manufactured according to available space and configuration inside the cocoon.
- **Compressed air tank**: a compressed air tank with control valves is placed in the cocoon in order to pressurise the spring adjustment tank, in order to compensate pressure losses. The pressure inside the compressed air tank will be 100-200 bar, which is in the range of common off-the-shelf pressurised air tank systems. The feeding time is relatively slow which is why all valves, and piping are no significant design challenges.
- **Winch or other mechanism**: for tide compensation and survivability mode under severe sea conditions, a winch unit (or alternative mechanism) is placed either on the bottom part of the cocoon, or into an external box, as described in section 3.1. It will equally be used for maintenance removal of the cocoon. Interfaces to upper part of cocoon and/or outside of device. Design details will be elaborated at a later stage.

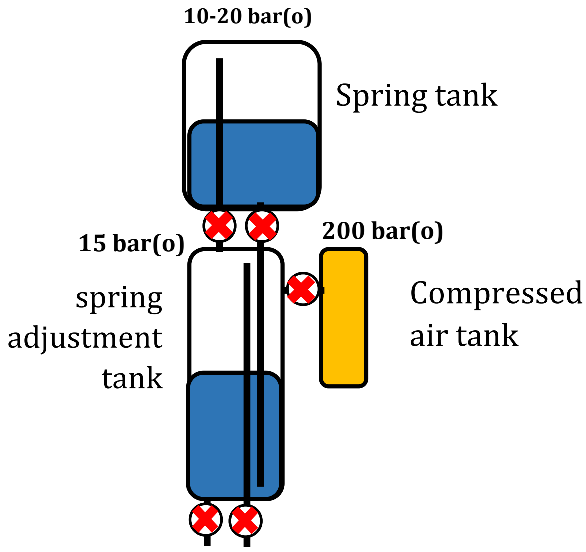


FIGURE 2: SCHEMATIC VIEW OF COCOON HOUSING VITAL COMPONENTS AND CONTROLS OF SYMPHONY

The spring tank inside the WEC acts as a spring and medium carrier for the PTO. The water/air ratio inside the spring tank influences the system's mass spring characteristics. During temperature or tidal changes, the water/air ratio needs to be adjusted in order to optimise the WEC's efficiency. This is done via an air pressure and a compressed air tank as illustrated in Figure 2.

The spring adjustment tank is used to tune the spring tank. The neutral pressure inside the spring tank is 15 bar. The neutral pressure is regulated using the compressed air tank and air outlet. The neutral pressure the spring tank is also 15 bar. The pressure inside the spring tank fluctuates between 10-20 bar each wave cycle. The pressure differential between the spring tank and the compensation tank is used to pump water or air between the two tanks. The compensation tank has five connections which are controlled externally in order to tune the spring tank when needed. The connections are the following: (i) compressed air connection, (ii) air connection to spring tank, (iii) water connection to spring tank, (iv) water inlet/outlet, (v) air inlet/outlet.

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 need to be designed under this consideration, which is part of a design exercise posterior to

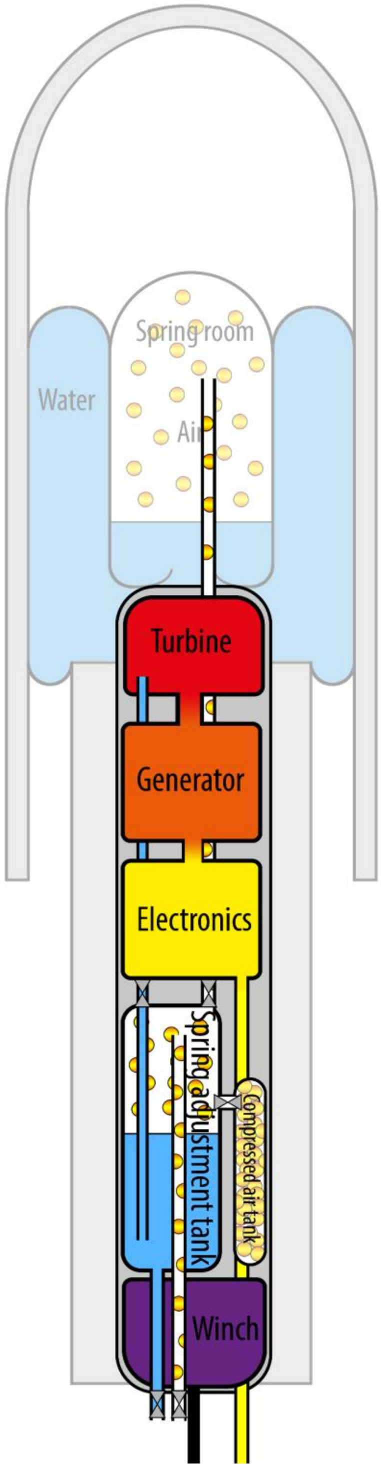


FIGURE 3: SCHEMATIC VIEW OF COCOON HOUSING VITAL COMPONENTS AND CONTROLS OF SYMPHONY

the WETFEET project.

In the following Figure 4, a summary of different required operational states and the corresponding valve positions are illustrated.

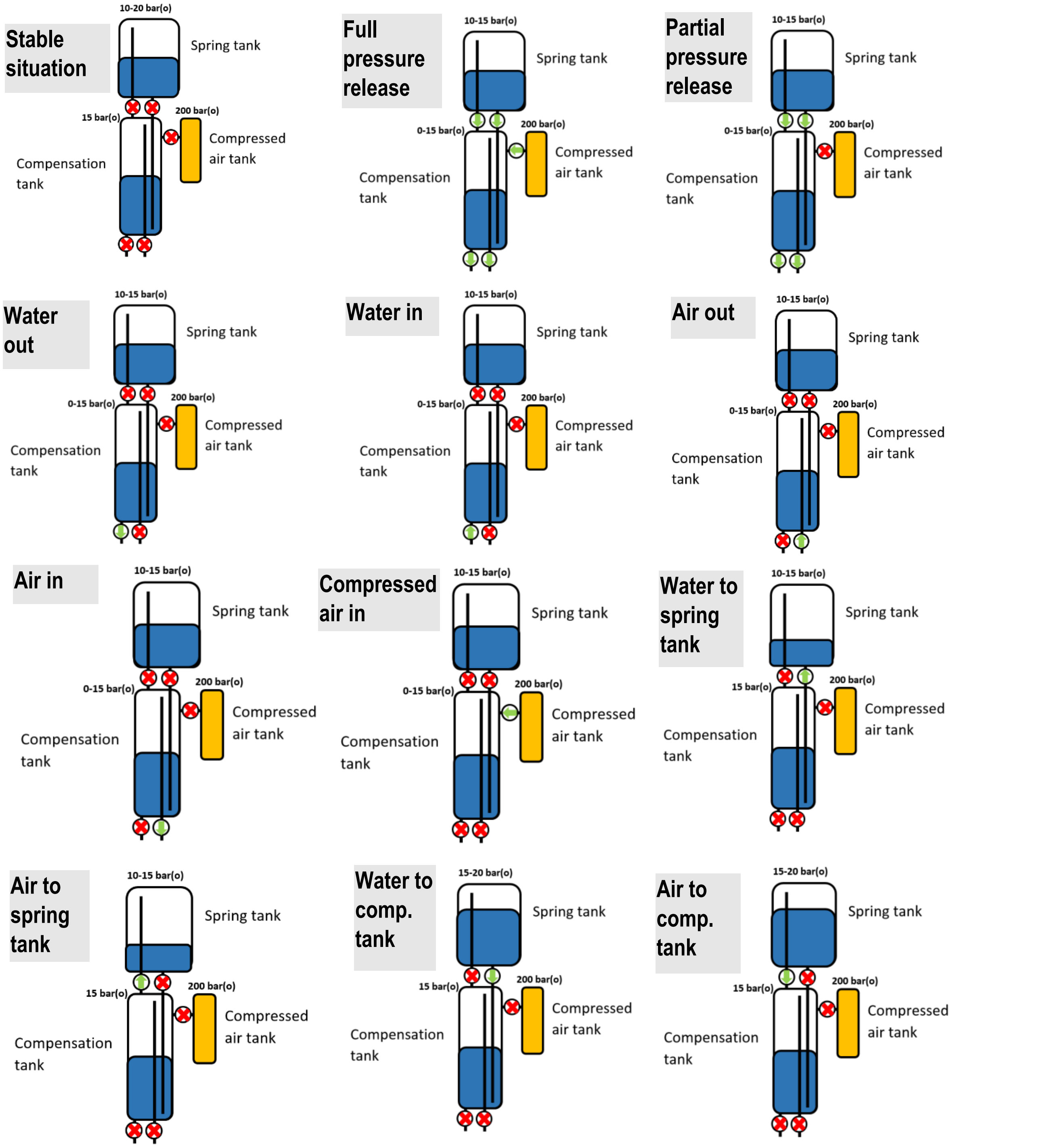


FIGURE 4: FUNCTIONAL SCHEMES FOR DIFFERENT TUNING SITUATIONS TO BE TACKLED BY THE COMPRESSED AIR AND COMPENSATION TANK CIRCUIT

2.2. Technical solutions for the integration of the cocoon components

Based on the functional requirements discussed in section 2.1, the central design challenge for the cocoon 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.

2.2.1. Guidance system

The control cocoon can be removed using a winch from the boat. A series of nylon guidance wheels are mounted on the exterior of the hull. The guidance wheels roll over the rails placed inside the hull of the Symphony in order to smoothly roll the cocoon in and out. Figure 5 shows the removal/insertion of the Symphony and a detailed image of the guidance system. It is very likely (section 3.1.3) the bottom part of Symphony will be mounted rigid to the mooring compensation box. The rigid part will contain an additional guiding system to align the cocoon before it is inserted into the device. Only with a good alignment the cocoon can be installed as indicated by the guidance wheels. See also the tank test results in section 3.2.

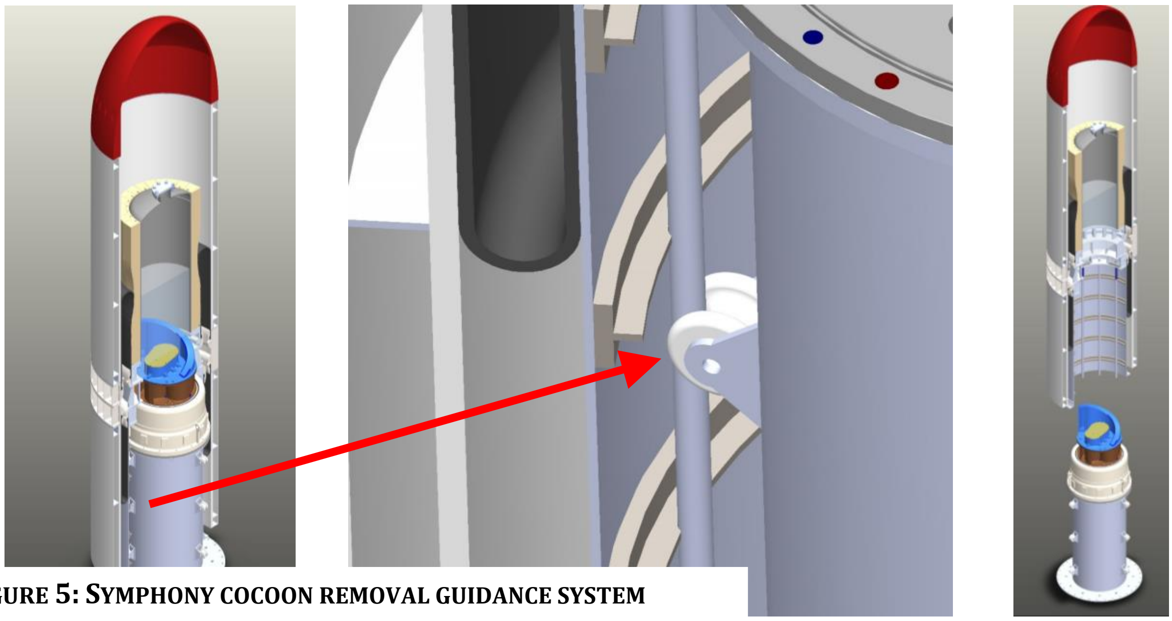


FIGURE 5: SYMPHONY COCOON REMOVAL GUIDANCE SYSTEM

2.2.2. Cocoon mount system

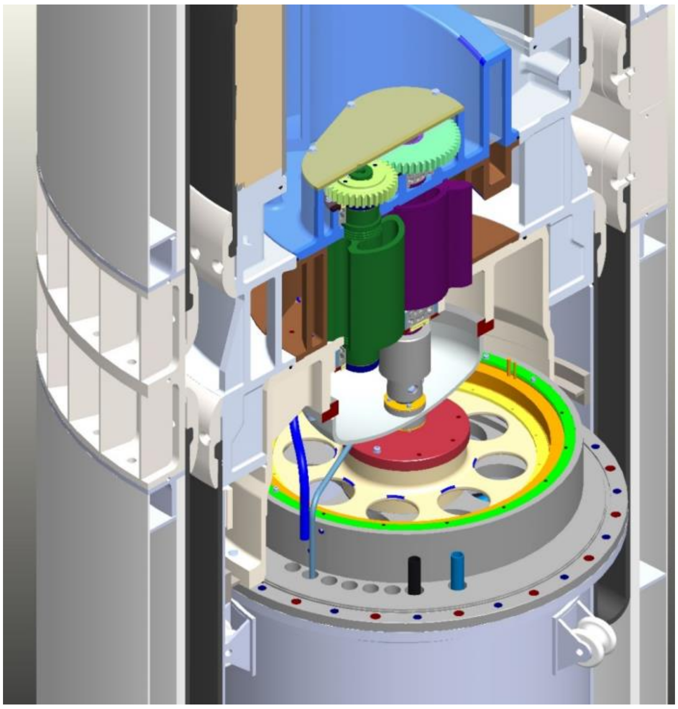
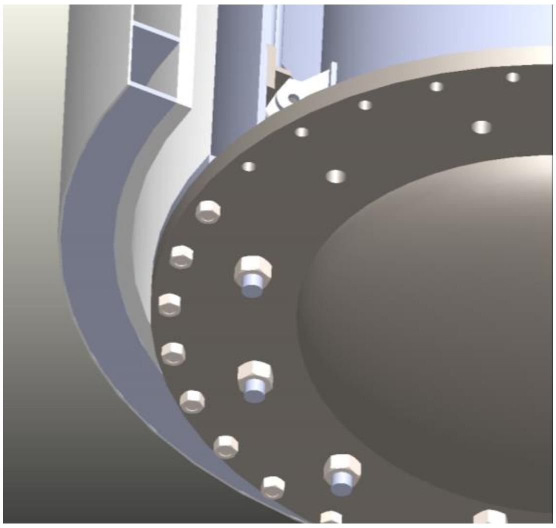



FIGURE 6: CROSS-SECTION VIEW OF THE INTERFACE COCOON TOP – TURBINE – BELLOW FRAME (LEFT); COCOON BOTTOM (RIGHT)

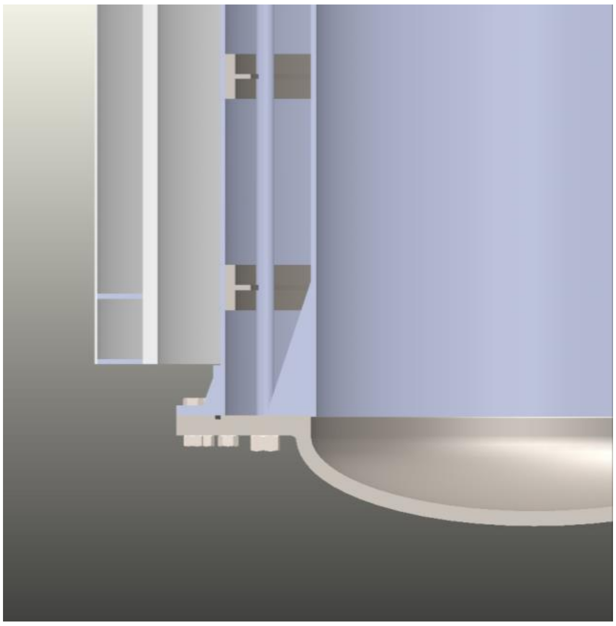
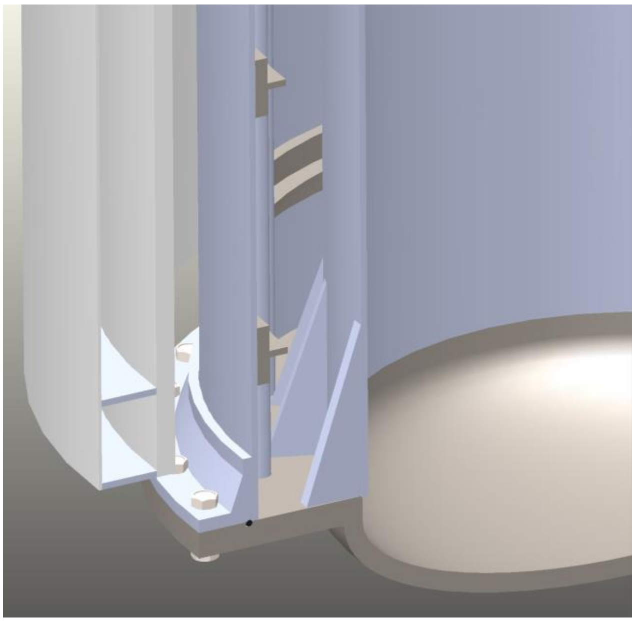



FIGURE 7: COCOON GUIDANCE RODS SECTION VIEW; ROTATIONAL GUIDANCE IS NOT DEFINED AT THIS STAGE.

2.2.3. Cocoon seal

The cocoon is sealed on top using a radial and axial seals (See Figure 8). The radial seal is the barrier between the spring tank and the turbine, which is mounted on the top end of the cocoon (as a key component potentially subject to maintenance, this is a design pre-requisite). The pressure differentials between these components is below 5 bar. The axial seal is the seal between the high-pressure side and the atmospheric pressure side. It is therefore required to withstand pressure differential in excess of 20 bar, in order to ensure stable over-pressure inside the device's primary PTO area. Rubber seals designed for this purpose are expected to be used.

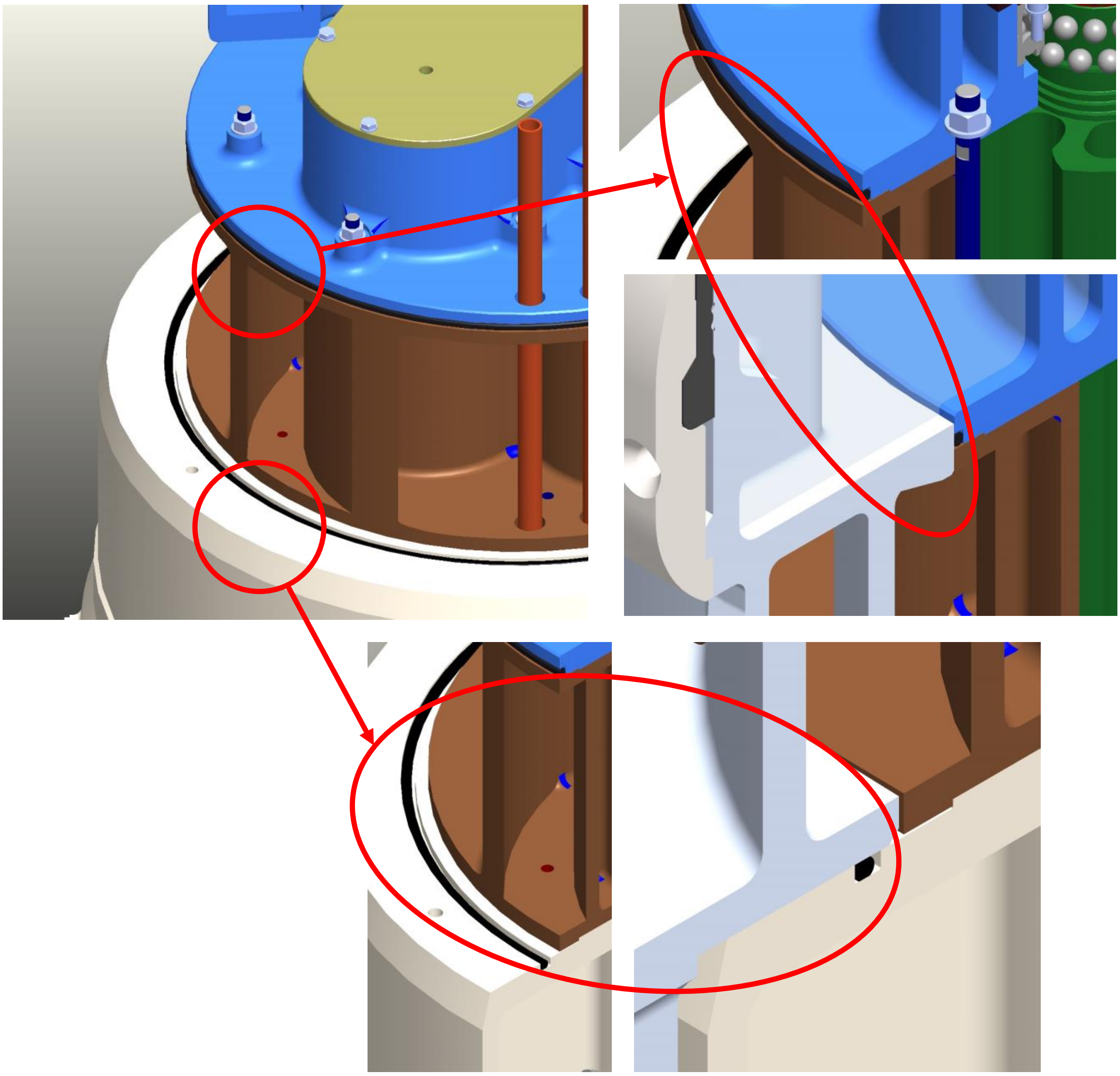


FIGURE 8: COCOON TOP SEALS (ABOVE, LEFT); COCOON RADIAL SEAL (ABOVE, RIGHT) AND AXIAL SEAL (BELOW)

2.2.4. Dynamic seals

The Symphony uses 2 dynamic seals to avoid the turbine PTO from leaking water. The pressure on the top side of the seal house is alternating between 15 and 25 bar. The chamber below the gear house is pressurised to minimize the pressure drop over the seals.

The top seal is the primary seal that holds most of the pressure. If the primary seal leaks, the secondary seal can serve as interim water barrier. The water between these seals flow to an external reservoir using a steam trap. Technical details for potential off-the-shelf models for the seals and the steam trap are shown in Appendix V. The steam trap allows to release water/condensate while keeping the (over) pressure (without letting the pressure drop).

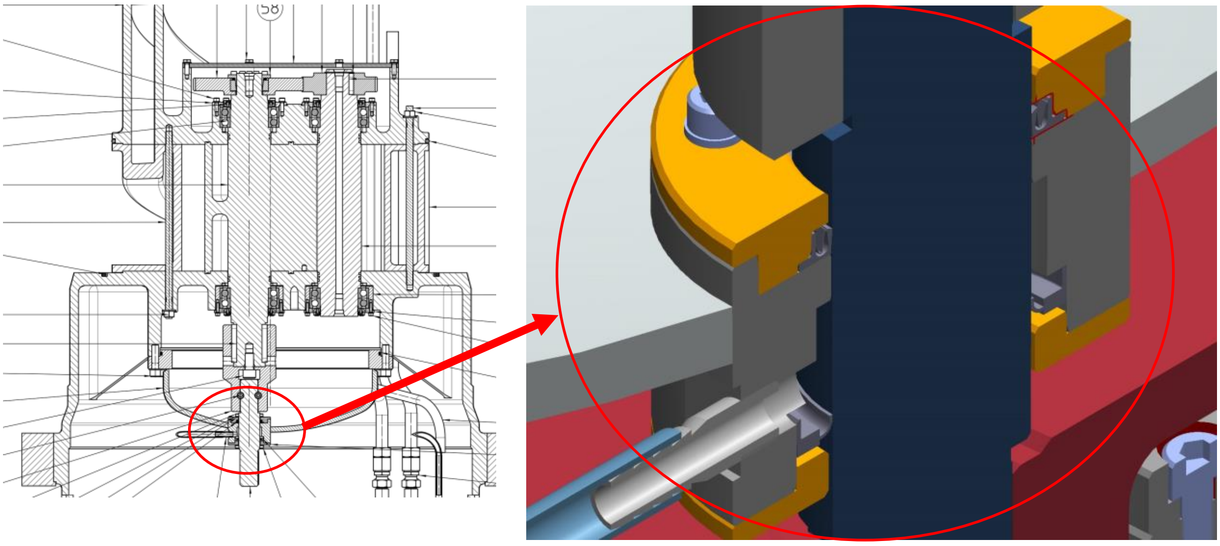


FIGURE 9: SEAL HOUSE POSITION (LEFT); DETAILED VIEW (RIGHT)

FIGURE 10: PRIMARY SEAL (LEFT); SECONDARY SEAL (CENTRE), AND FLOAT STEAM TRAP (RIGHT)

The primary seal is a PTFE, Poly-aramid, mineral fibre, lubricant and graphite filled rubber type. This type of material has excellent wear and sealing properties at a low friction rate for PTO enclosures. This high-end seal is chosen to minimize maintenance interval. The secondary seal is a regular lip seal. The purpose of the seal is to protect the generator and electronics from the possible small leaks of the primary seal. The lip seal is not able to withhold large pressure differentials but it has a lower friction rate at low pressure differentials. Because the secondary lip seal should withhold less pressure difference, this type of seal is chosen.

2.2.5. Structural details of the control cocoon

The control cocoon needs to be sealed while the turbine is operational. The pressure from the spring tank acts on the control cocoon. FEM analysis of the key structural elements of the control cocoon was conducted, and the results are reported in Appendixes II and III.

The total weight of the cocoon is at this stage estimated to be in the range of 200 ton. With a total Symphony WEC weight (in air) of approximately 600 ton, the resulting cocoon to device weight ratio is approximately one to three.

Cocoon specs	
Total weight of the cocoon (estimated):	200 t
Total device weight (estimated):	600 t
Cocoon to device weight ratio:	1:3
Length of the control cocoon:	12m
Diameter of the control cocoon:	4m

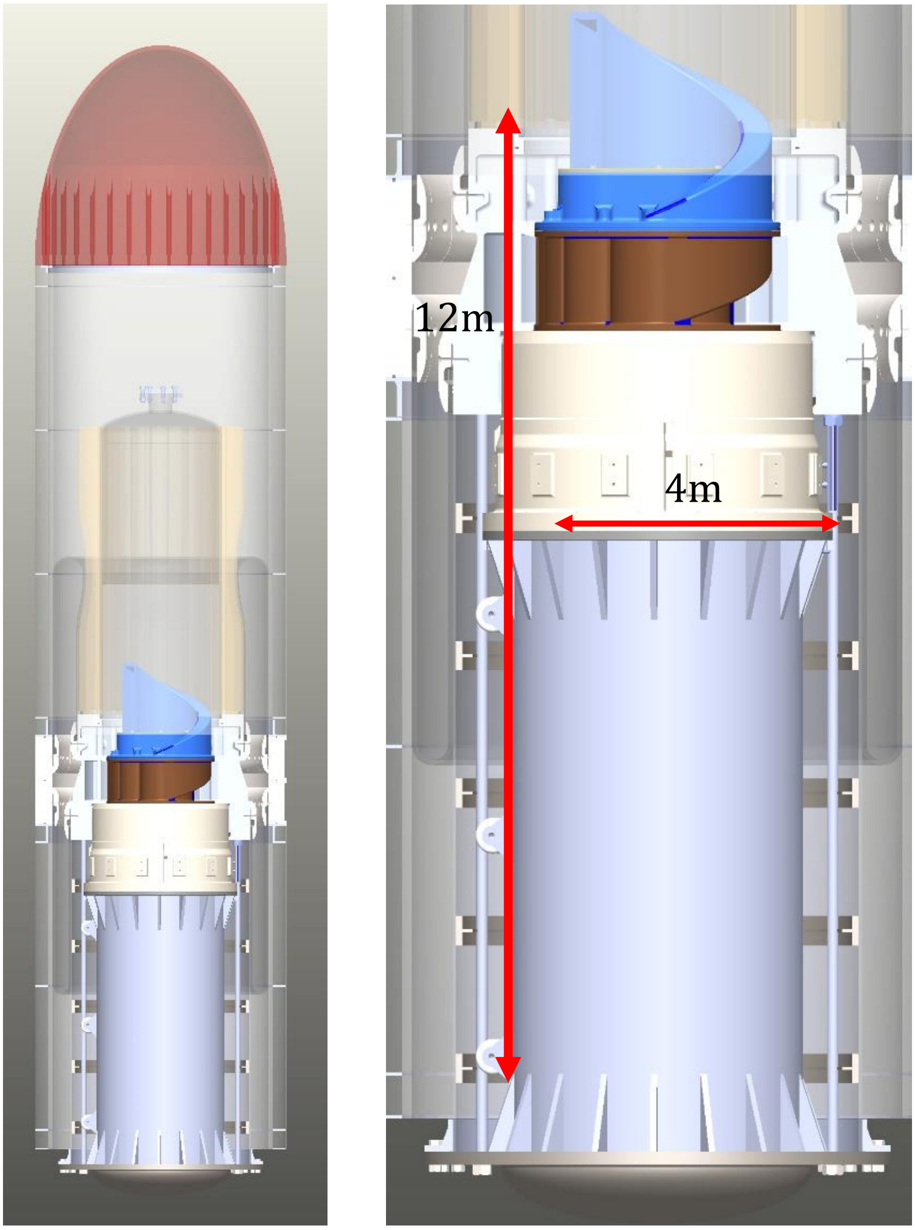
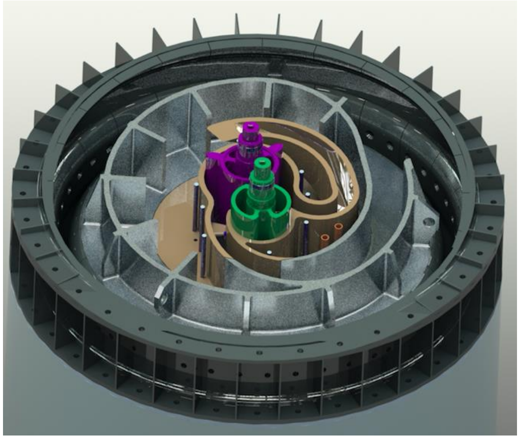


Figure 11: Expected dimensions and weights for control (left), general view with turbine mounted on top (blue and brown), inserted in Symphony WEC (centre), zoom of cocoon (right)

2.2.6. Other elements

- **Turbine:** the turbine is considered as a critical component and therefore placed inside the cocoon. It has moving components and bearings which need checks or replacement within 5 years of operation, in addition to a dedicated inspection/monitoring strategy. Details of this are part of the work at later stage, and the detailed design of the purpose-made bidirectional water turbine for Symphony is part of WP4 of the WETFEET project.



- **FIGURE 12: THE PROTOTYPE TURBINE**

- **Valves:** as part of the control cocoon, automatic valves are installed between interacting vessels of the air spring tuning system.
- **Generator:** the generator is designed to withhold 10-year maintenance free operation. Therefore, the generator is not necessarily a critical component, but is located underneath the turbine. An off-the-shelf option is a 1 MW permanent magnet machine (like those in Appendix VI, but custom made the Symphony device at 350 RPM). Research on using an air-cored generator is ongoing, and preliminary conclusions indicate that the air cored direct drive generator will be the final choice. However, this research is not finalized at this stage, which is why for the time being this model is used in the design.

FIGURE 13: THE SWITCH 1MW GENERATOR

- **Convertors inside:** all power converters and control PLCs with SCADA interfaces are in the cocoon, with additional insulation. Off-the-shelf components will be used according to the generator and control instrumentation.
- **Control instrumentation:** to enable the air/water system being continuously tuned is the key to smooth Symphony WEC operation. For this, set points of control algorithms should be verified and measurements of different physical variables measured. Most of these measurements are placed inside the cocoon, as illustrated in Figure 14.

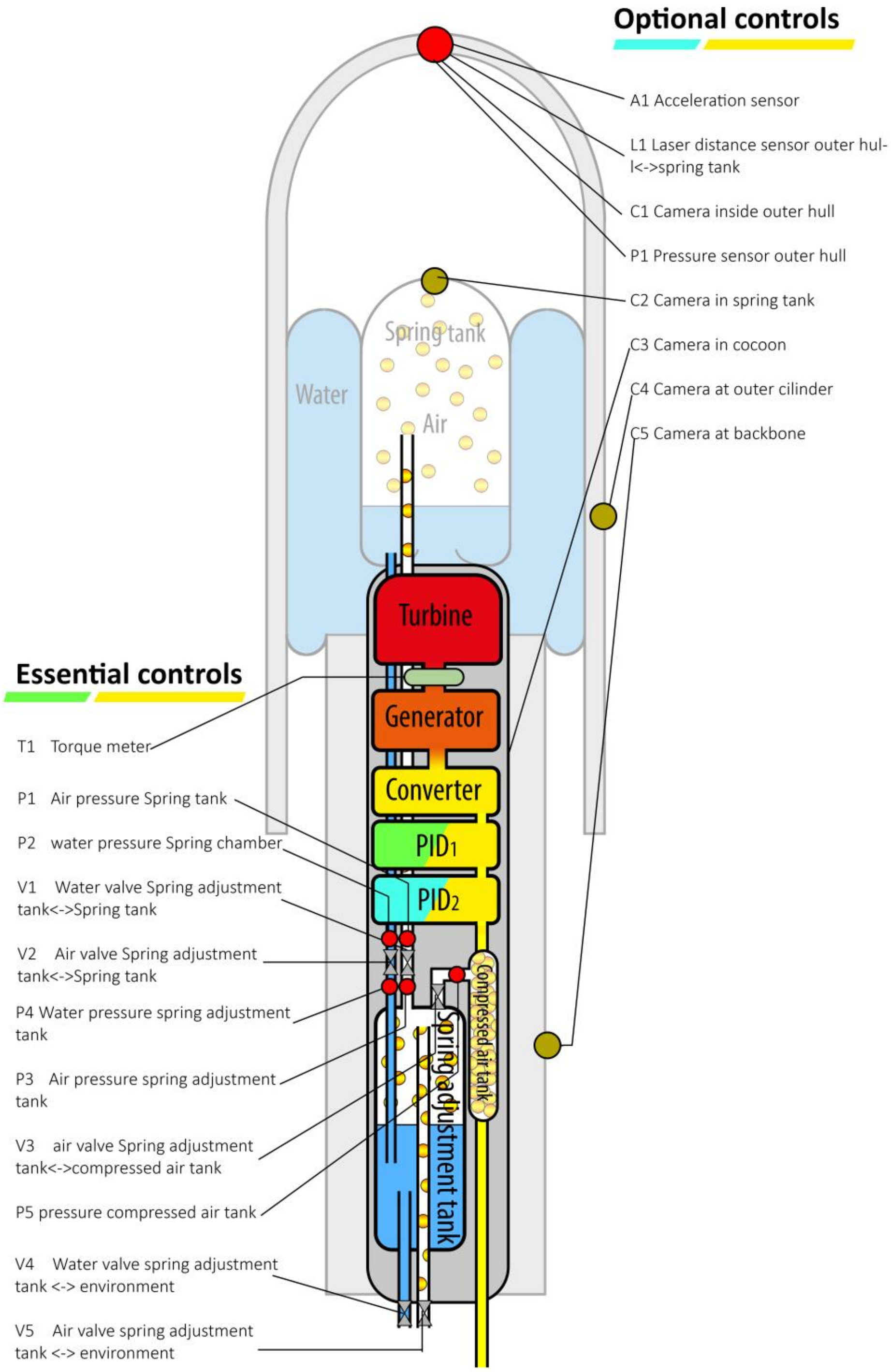


FIGURE 14: ESSENTIAL AND DESIRABLE CONTROL INSTRUMENTATION FOR THE SYMPHONY WEC

3. CONTROL COCOON REMOVAL TESTS

As part of the WETFEET project, a series of tank tests at the FloWave Ocean Energy Research Facility in Edinburgh were conducted, to address 3 major conceptual issues for the Symphony WEC:

(i) Validation of different mooring types.
(ii) Validation of the cocoon removal procedure under wave action.
(iii) Comparison of hydrodynamic behaviour of the Symphony with and without cocoon.

In the following, the different mooring types used in the test configuration are explained.

3.1. Mooring and test configuration

Each of the configurations is expected to have a direct impact on the cocoon removal strategy, whilst also the seakeeping characteristics of Symphony WEC may be affected by the choice. Therefore, it was deemed necessary to perform the tank trials for three different configurations. The three mooring type configurations tested where (i) a simple tension leg mooring, (ii) a tension leg with restoring lines and a tension leg with restoring legs and a stiff extended frame.

3.1.1. Simple tension Leg

A bare single tension leg as mooring would be the least costly and most straight-forward way of mooring the Symphony. The downside of this setup is that there is no redundancy in case of failures, and it can be expected that yaw movements (twisting of the cylindrical WEC around its vertical shaft) may become critical in certain sea states. In this mooring setup, the tension leg does also not restore movements around the horizontal axes, pitch and roll, which is why in general large displacements are expected during possible resonance frequency's and large sea states.

Single line tension leg, seabed ballast anchored.

FIGURE 15: SIMPLE TENSION LEG SETUP

3.1.2. Tension Leg with restoring lines and mooring compensation box

In this configuration a box (in the following shown in yellow) is placed in the water column between the Symphony and the ocean surface. This setup reduces displacement using restoring lines, and adds station keeping redundancy in case of failure. Due to the system being entirely based on mooring lines, the Symphony WEC can still move independently from the mooring compensation box. The mooring compensation box is a buoy which compensates the weight of the anchors and has a tide compensation device inside. Tide compensation is adjusting the height in the water column relative to the average water surface, to have a relative steady permanent water column on top of the floater.

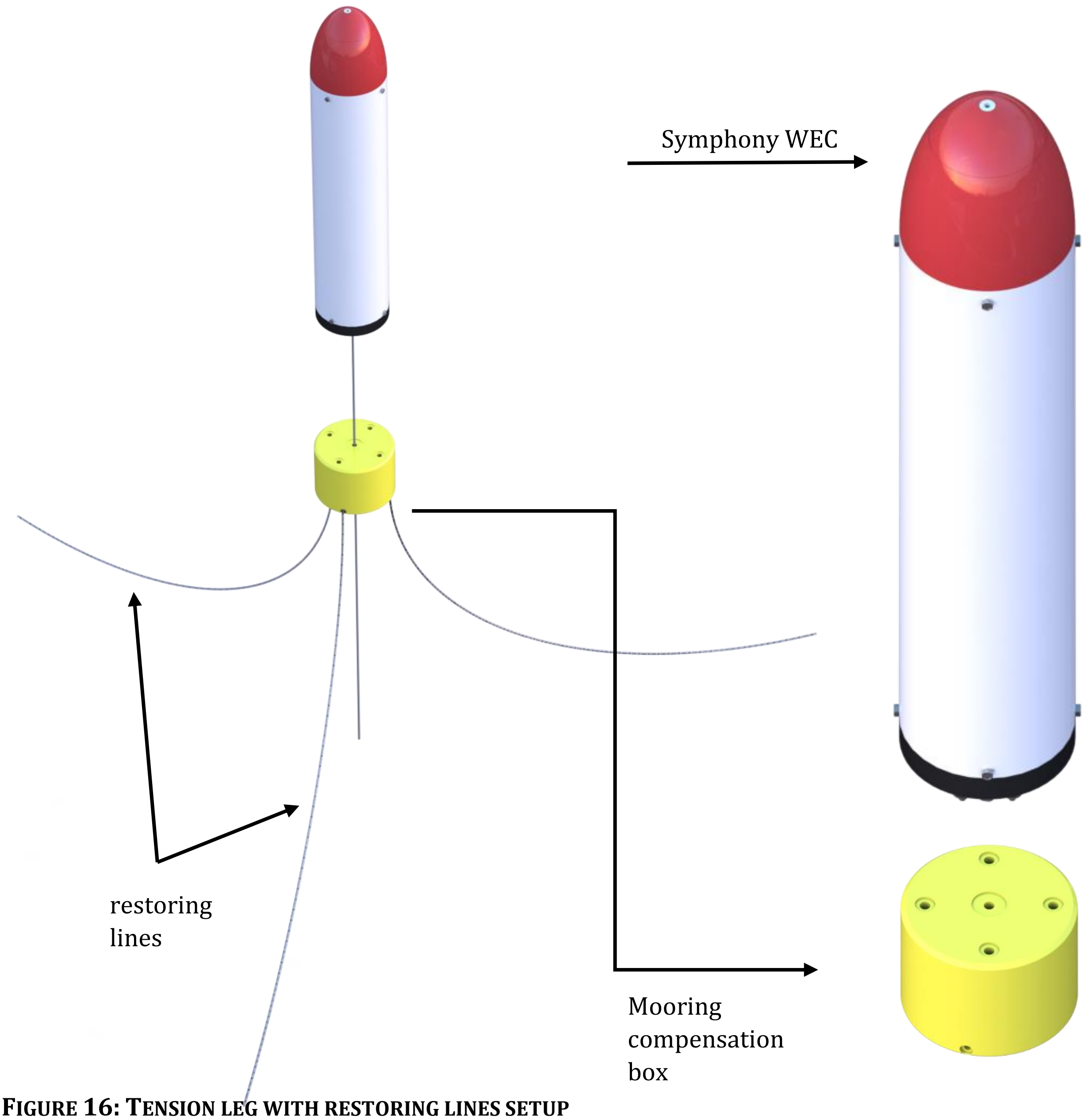


FIGURE 16: TENSION LEG WITH RESTORING LINES SETUP

3.1.3. Tension leg with restoring legs and a stiff extended frame

Based on the same configuration as described in the previous section, here the mooring compensation box is connected to the bottom of the Symphony WEC via a rigid extension frame structure. This setup is expected to further reduce the effect of yaw, and can be an important element for facilitating cocoon removal and re-insertion. Unless the tank trials result in the indication that these effects are not relevant, this is the foreseen configuration for the further development.

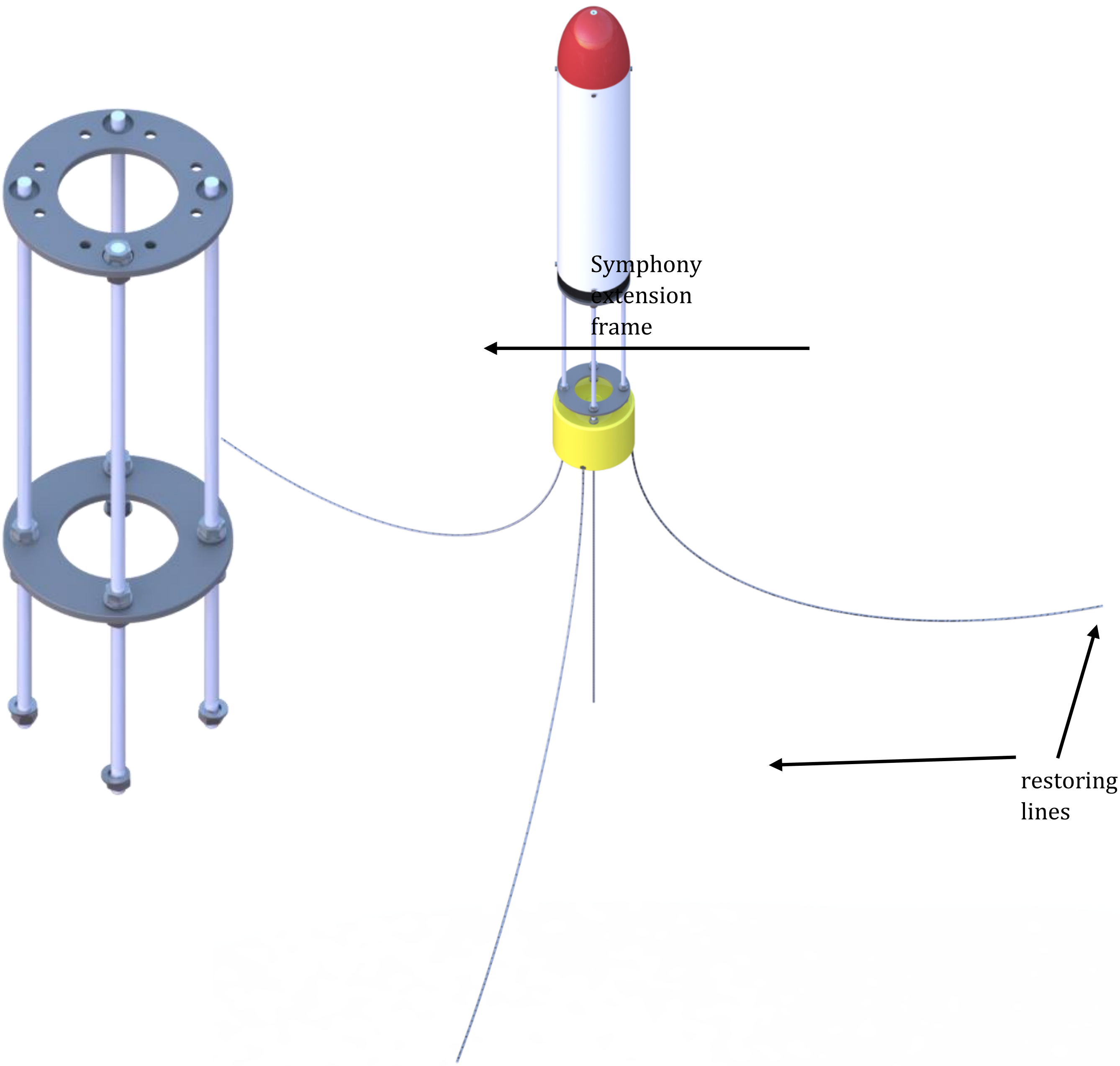


FIGURE 17: TENSION LEG WITH RESTORING LEGS AND A RIGID EXTENDED FRAME

3.2. Tank experiment observations

A physical scale model of a 6m diameter Symphony device was manufactured and tested in the FloWave Ocean Research Centre of Edinburgh. The scale was limited to 1:37.5, due to the maximum depth of the tank and the relatively long Symphony structure and operational depth. The tank trial setup is detailed in Appendix I, showing the main parameters and dimensions.

During these trials different mooring setups have been compared, and the physical cocoon removal and insertion during different sea states was demonstrated. In addition, the hydrodynamic performance of the Symphony with the cocoon removed has been validated. The latter was only possible to document in a somewhat qualitative way (time and resources were not sufficient to implement specific sensor system), allowing to get a first solid indication that with removed control cocoon, the Symphony becomes more stable.

The Symphony tank test model has a removable inner mass component which allows adjusting the hydrodynamic behavior. This replicates the effect of removing the control cocoon of the Symphony wave energy converter, thus allowing to interpret the tank trial observations as giving confidence for not causing any unforeseen and undesirable hydrodynamic instability by removing the cocoon.

With respect to the comparison of the different mooring configurations presented in section 3.1, the measurement results for yaw, pitch and roll in significant wave heights of 2, 5 and 11m are illustrated in the time domain in section 3.3, and briefly discussed in the end of that section.

In the present section, focus lies on the feasibility of the actual cocoon removal- and re-insertion exercise in different sea states. The objective of the cocoon removal sequence was to get a first indication in which sea states such an operation could be feasible.

Several simplifications have been introduced for this purpose, starting from a pre-fixed pulley system, to pull the cocoon out and back in without having to change the model setup. Also, the cocoon interface with the Symphony structure has been modeled as two plain cylindrical surfaces, instead of detailing the guide rails and -wheels as described in section 2.2.1. Also, no radial cocoon guiding was implemented, which in real sea environment will be necessary, in order to guide the wheels into the right position on the rails on the inside perimeter of the WEC.

In the following Figure 18, the cocoon removal of the Symphony is demonstrated at a scaled sea state of H_s = 2m. In Figure 19, the cocoon insertion of the Symphony is demonstrated in the same conditions.

Successful cocoon operations were possible in the tank environment up to sea states with H_s = 5m. Various directions of tidal current was applied to the model during cocoon removal. Overall, the observations give confidence to further develop the cocoon removal and re-insertion with the Symphony WEC remaining moored, as future O&M strategy.

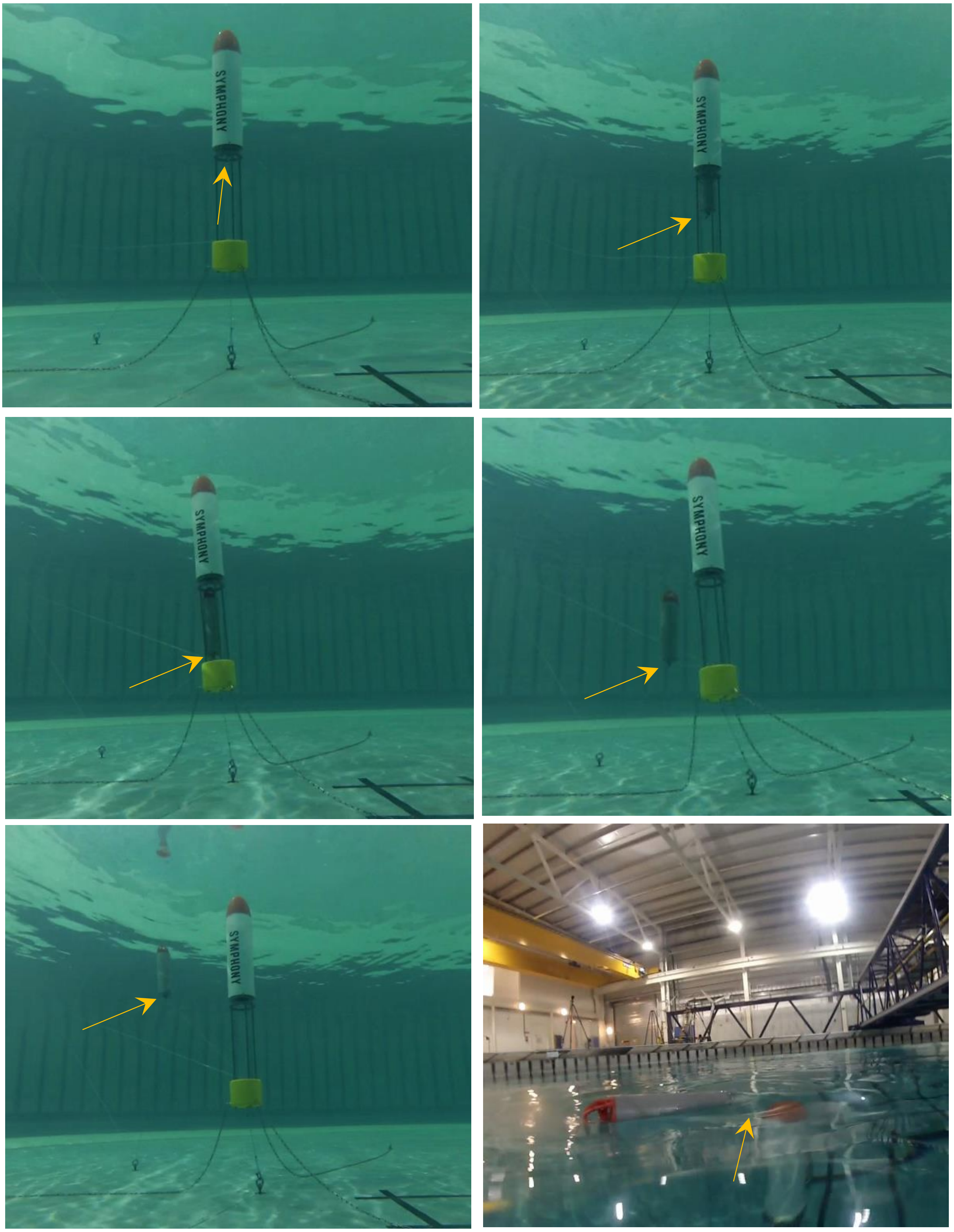


FIGURE 18: COCOON REMOVAL SEQUENCE AT HS=2M, TE=10S. THE ORANGE ARROW POINTS AT THE BOTTOM OF THE COCOON.

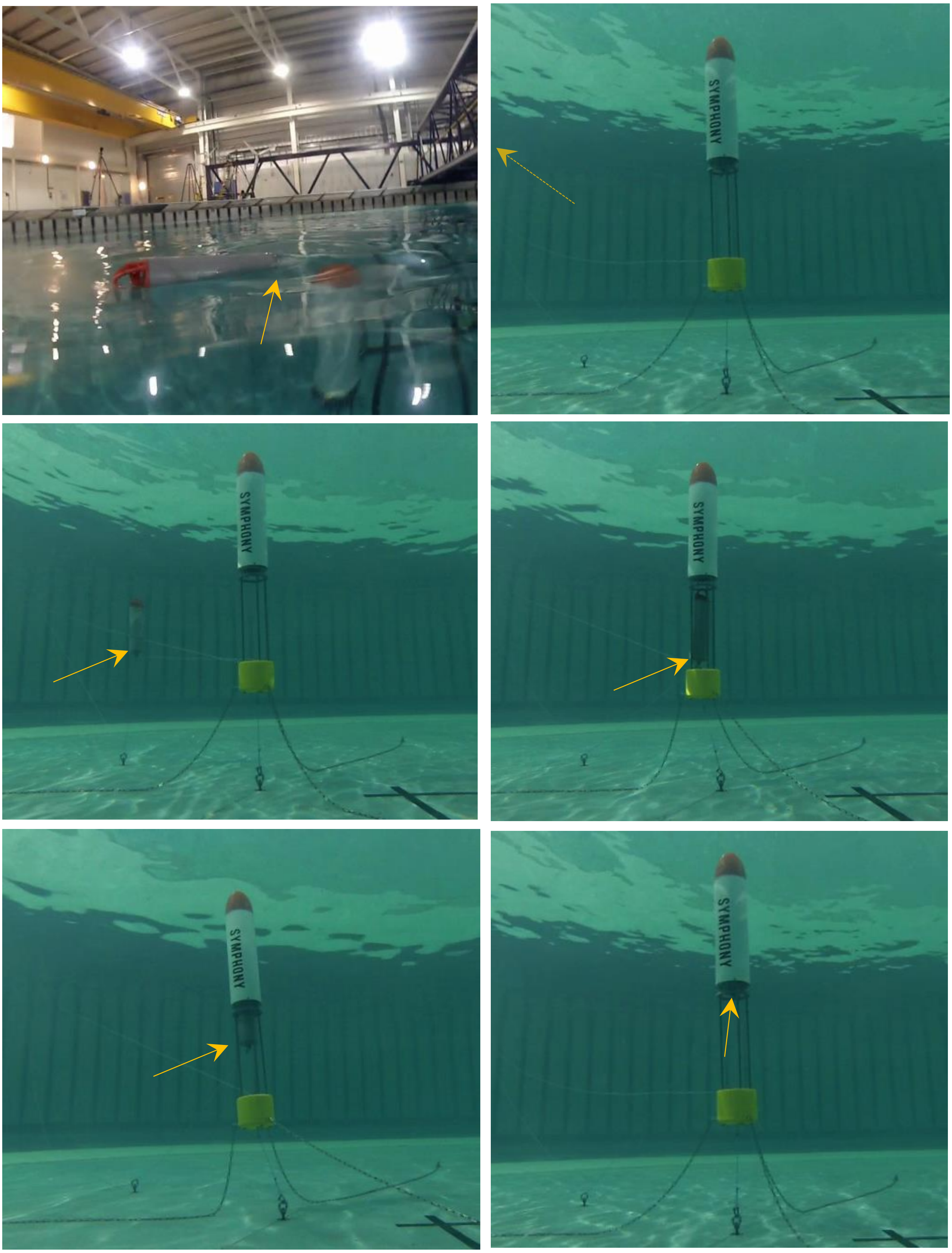


FIGURE 19: COCOON INSERTION SEQUENCE. THE ORANGE ARROW POINTS AT THE BOTTOM OF THE COCOON.

3.3. Measurements and interpretation

As mentioned in the previous section, the results of the yaw, pitch and roll angles are shown for 3 different types of mooring setups and 3 different sea states, for each mooring configuration in separate. The most common sea state H_s =2m, the biggest operational sea state H_s = 5m and a stormy sea state H_s = 11m.

3.3.1. Simple tension Leg

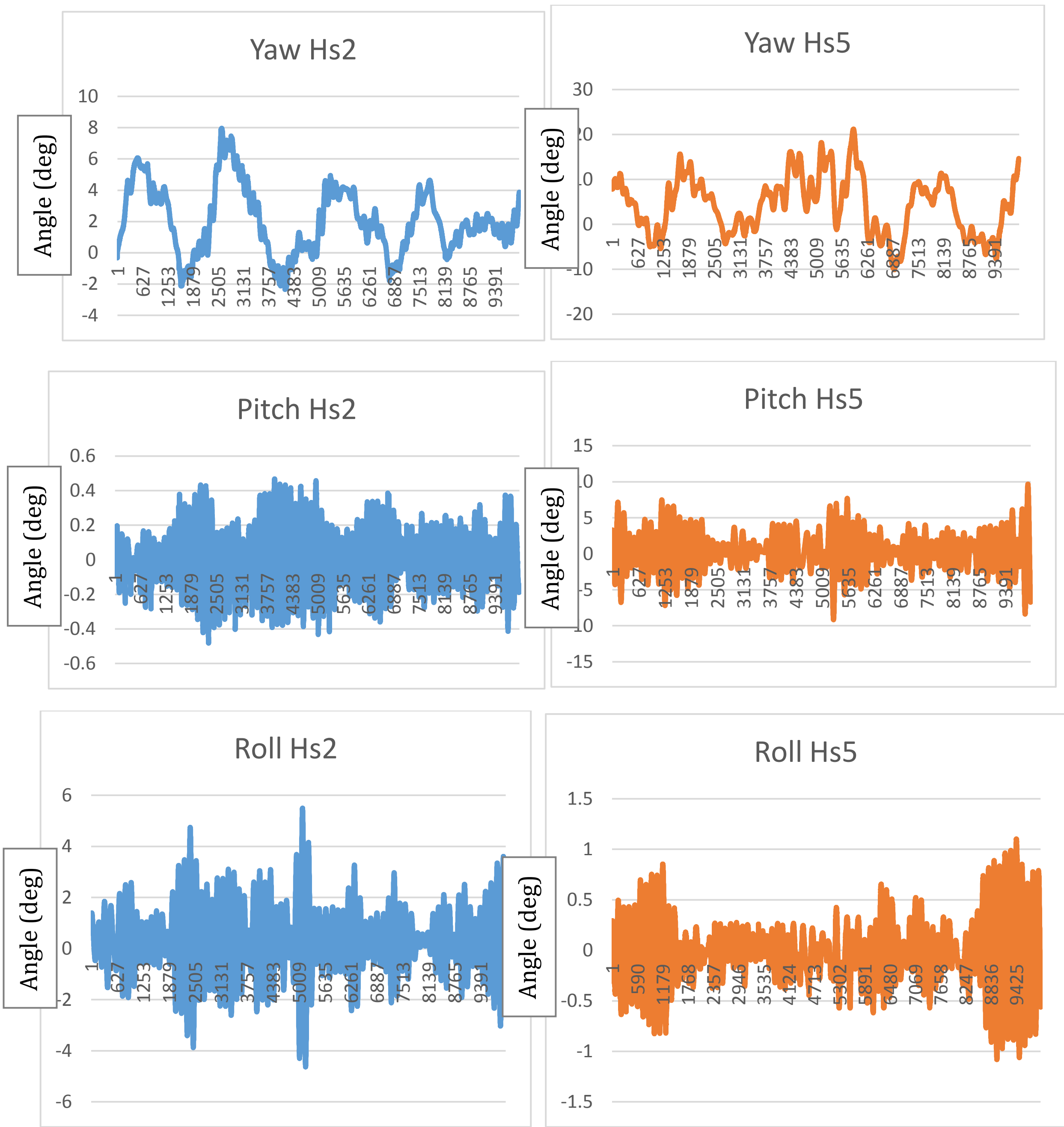


FIGURE 20: STABILITY GRAPHS OF THE TENSION LEG SETUP IN TYPICAL AND MAXIMUM OPERATIONAL SEA STATE

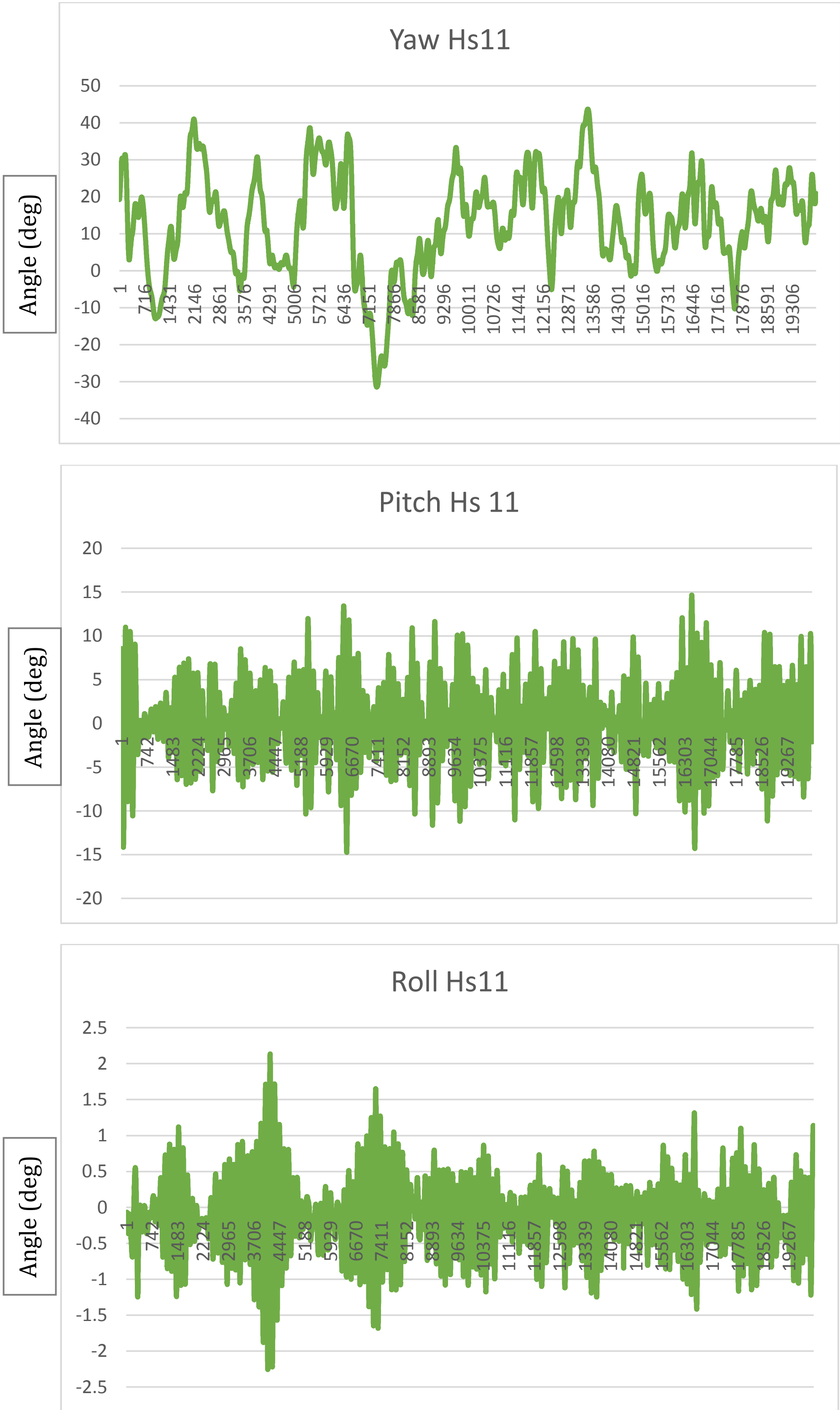


FIGURE 21: STABILITY GRAPHS OF THE TENSION LEG SETUP DURING EXTREME SEA STATE HS= 11M

3.3.2. Tension Leg with restoring lines and mooring compensation box

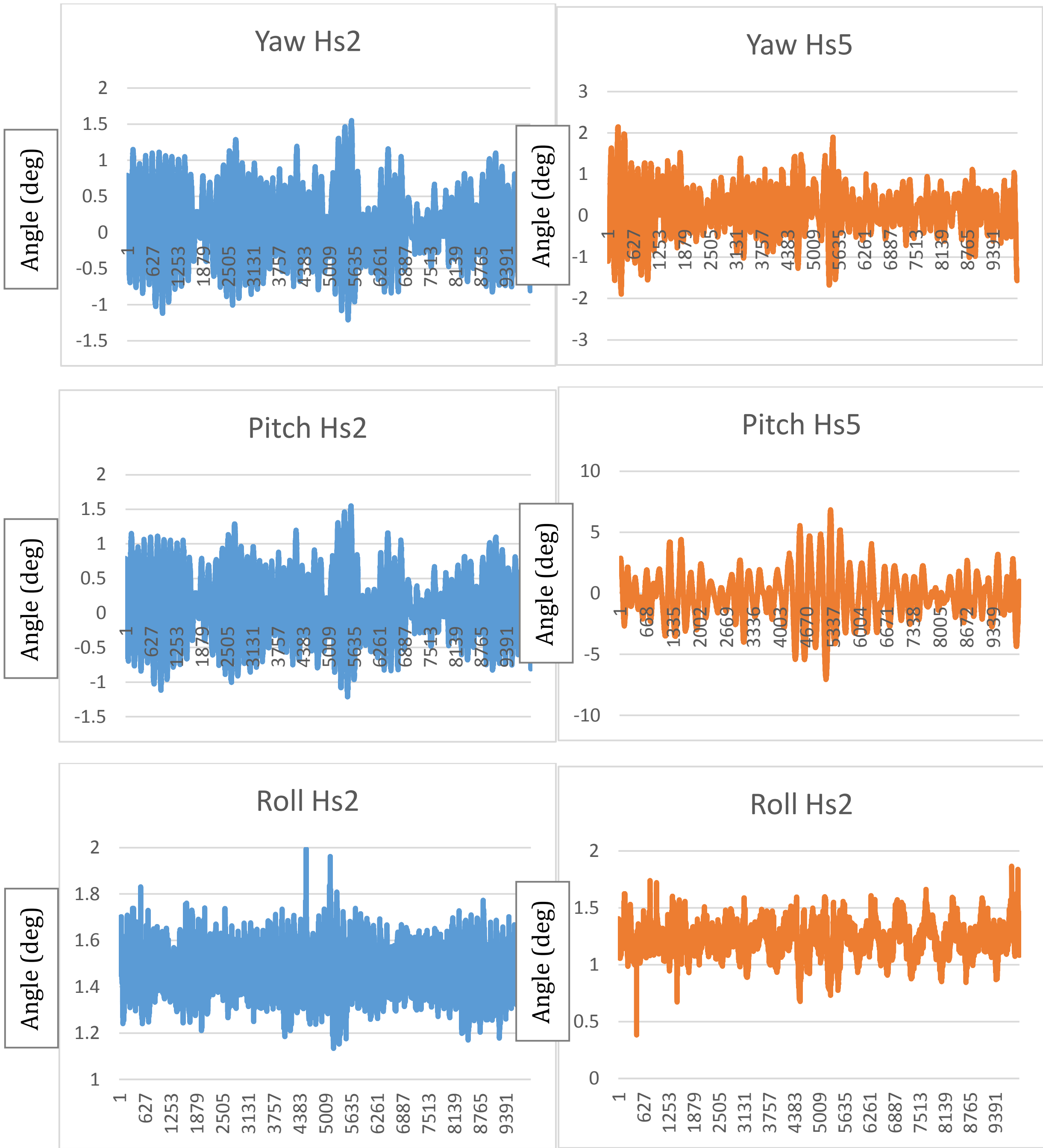


FIGURE 22: STABILITY GRAPHS OF THE TENSION LEG WITH RESTORING LINES SETUP IN TYPICAL AND MAXIMUM OPERATIONAL SEA STATE

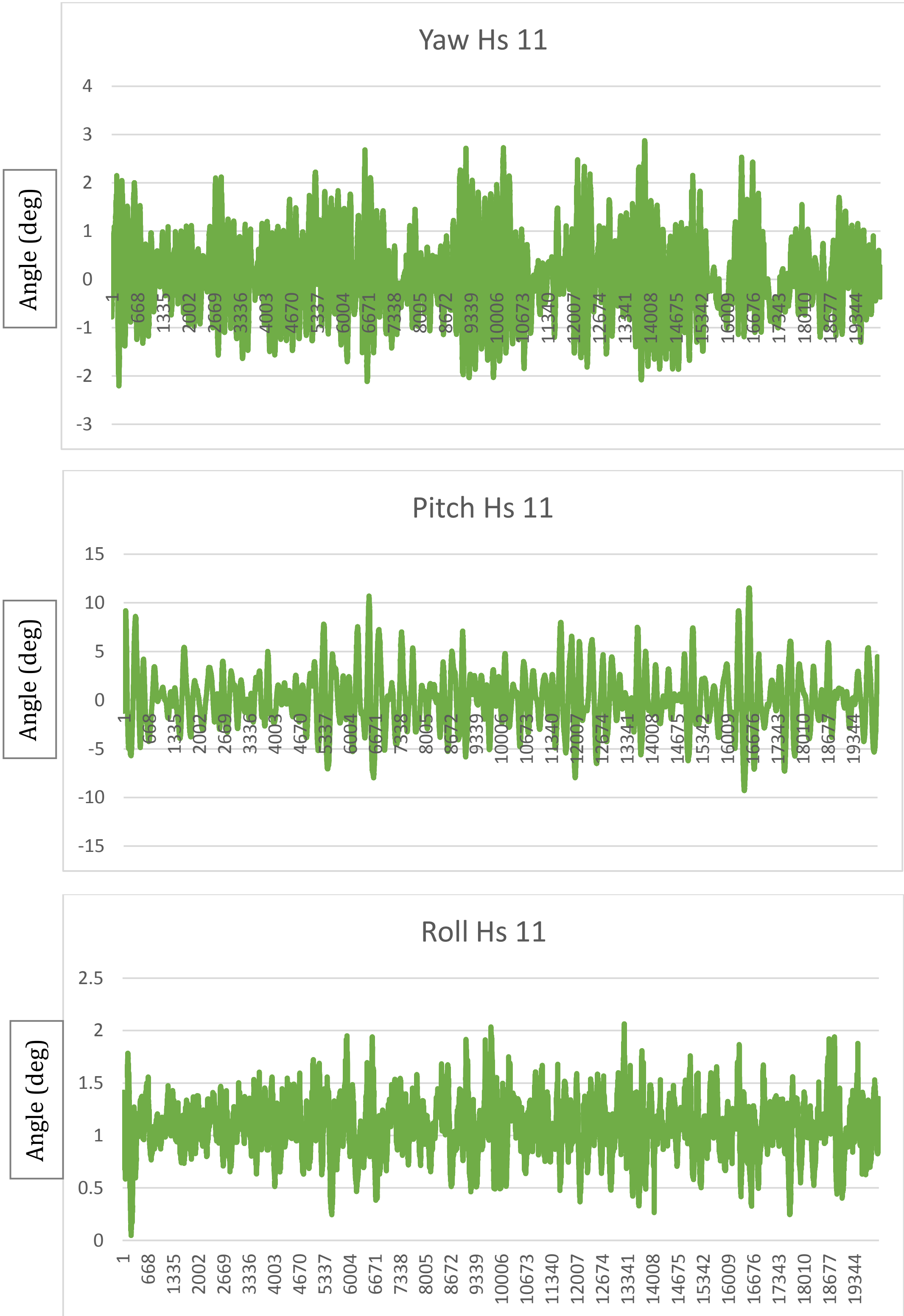


FIGURE 23: STABILITY GRAPHS OF THE TENSION LEG WITH RESTORING LINES SETUP DURING EXTREME SEA STATE HS= 11M

3.3.3. Tension leg with restoring legs and a stiff extended frame

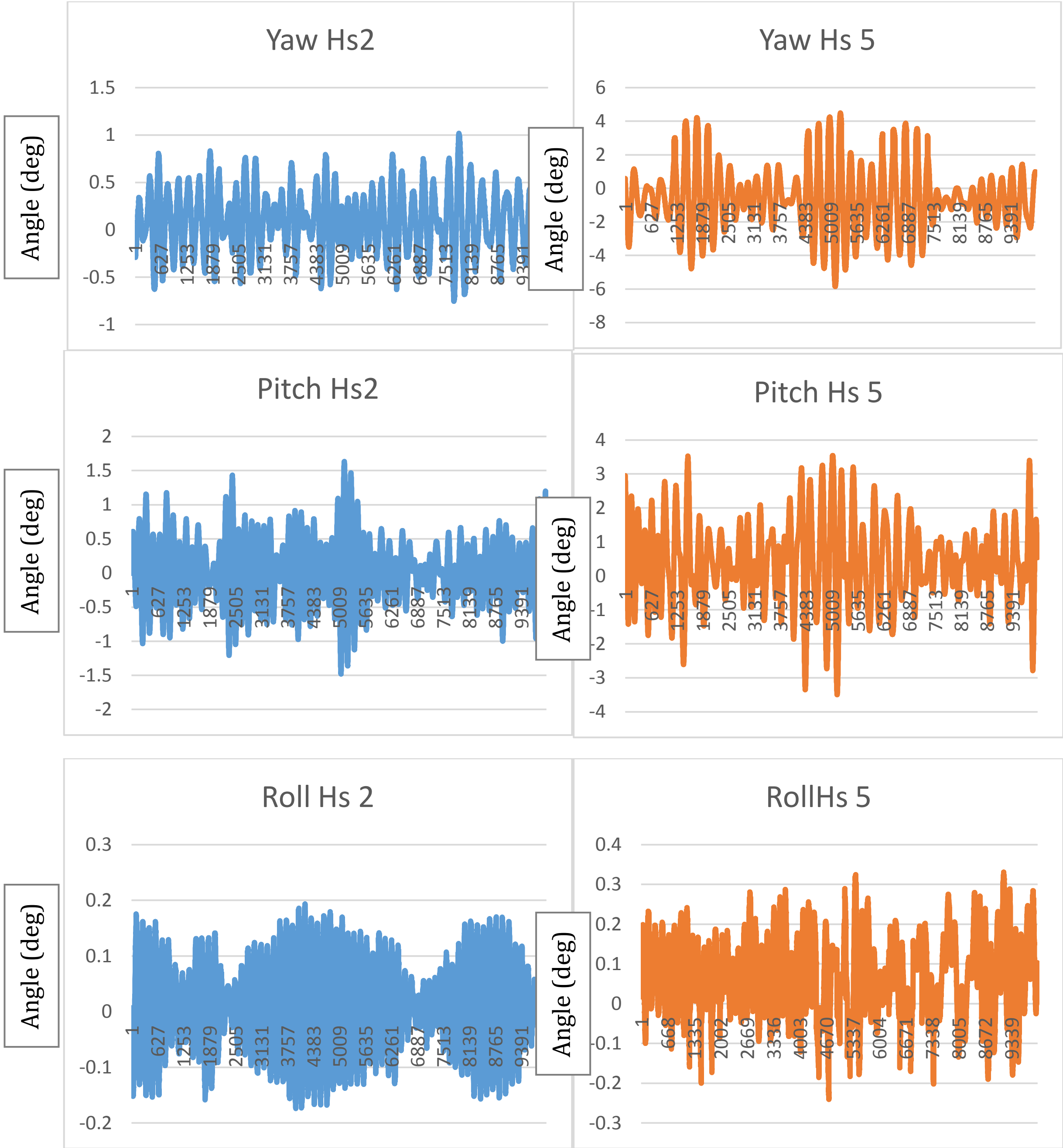


FIGURE 24: STABILITY GRAPHS OF THE TENSION LEG WITH RESTORING LINES AND RIGID EXTENDED FRAME SETUP IN TYPICAL AND MAXIMUM OPERATIONAL SEA STATE

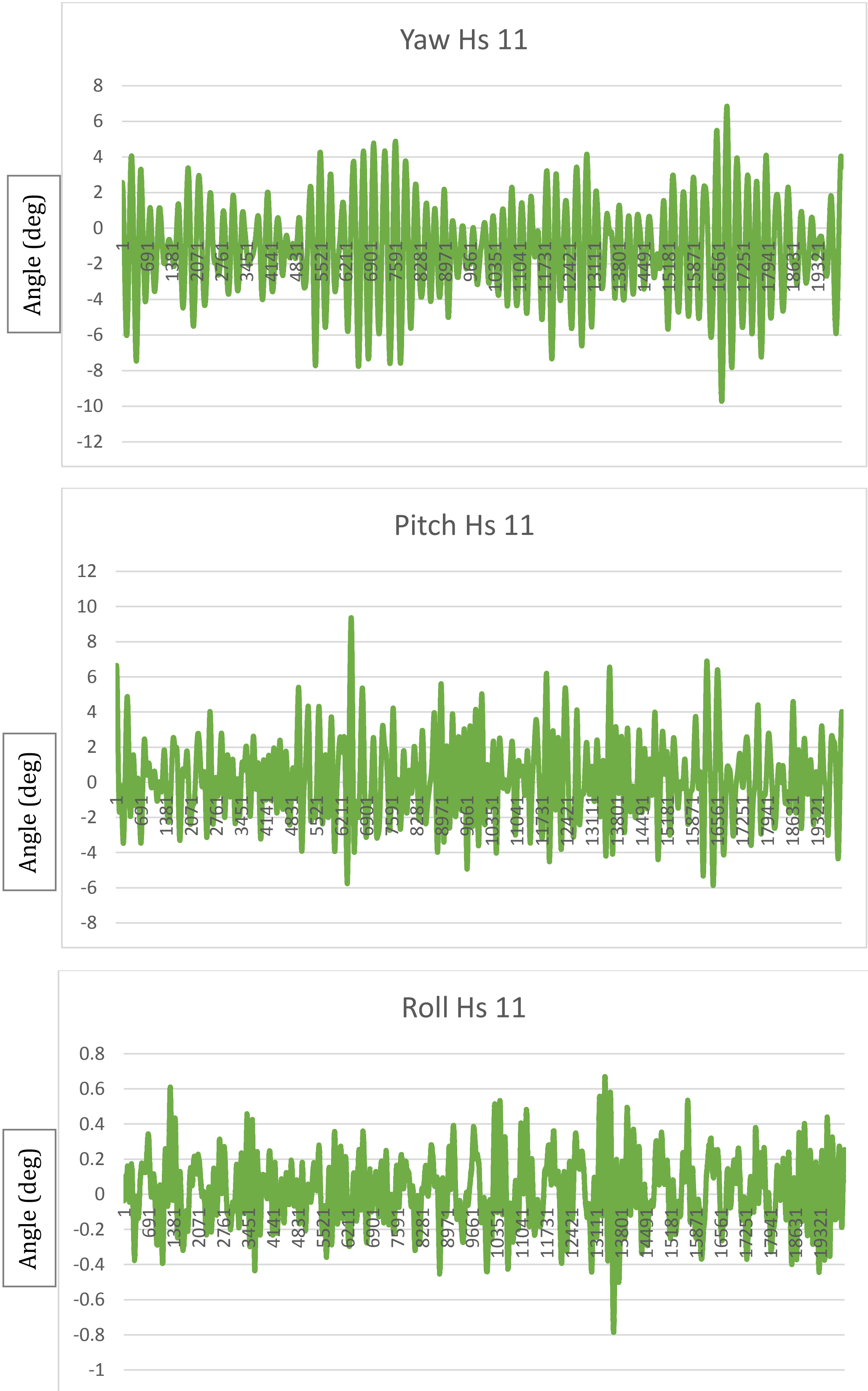


FIGURE 25: STABILITY GRAPHS OF THE TENSION LEG WITH RESTORING LINES AND STIFF EXTENDED FRAME SETUP DURING EXTREME SEA STATE HS= 11M.

3.3.4. Stability comparison

In Table 1 below, the ranges of values observed in Figure 20 to Figure 25 are shown, organized into the three different mooring configurations and the yaw, pitch and roll angle for each case.

TABLE 1: TANK TEST RESULT SUMMARY OF SYMPHONY MOVEMENTS IN DIFFERENT SEA STATES AND MOORING CONFIGURATIONS

H_s = 2m	Simple tension leg		Tension leg with restoring lines		Tension leg with restoring lines and extended frame	
YAW	Range: -2.0 -> 8.0	(deg)	Range: -1.0 -> 1.5	(deg)	Range: -0.7 -> 1.0	(deg)
PITCH	Range: -0.4 ->0.4	(deg)	Range: -1.0 -> 1.5	(deg)	Range: -1.5 -> 1.5	(deg)
ROLL	Range: -4.0 -> 6.0	(deg)	Range: -1.2 -> 2.0	(deg)	Range: -0.2 -> 0.2	(deg)
H_s = 5m	**Simple tension leg**		**Tension leg with restoring lines**		**Tension leg with restoring lines and extended frame**	
YAW	Range: -10 -> 20	(deg)	Range: -2.0 -> 2.0	(deg)	Range: -6.0 -> 4.0	(deg)
PITCH	Range: -10 -> 10	(deg)	Range: -7.0 -> 6.0	(deg)	Range: -3.5 -> 3.5	(deg)
ROLL	Range: -1.0 -> 1.0	(deg)	Range: -0.6 -> 1.8	(deg)	Range: -0.2 -> 0.3	(deg)
H_s = 11m	**Simple tension leg**		**Tension leg with restoring lines**		**Tension leg with restoring lines and extended frame**	
YAW	Range: -30 -> 45	(deg)	Range: -2.0 -> 3.0	(deg)	Range: -10 -> 7	(deg)
PITCH	Range: -15 ->15	(deg)	Range: -10 -> 12	(deg)	Range: -6.0 -> 8.0	(deg)
ROLL	Range: -2.3 -> 2.1	(deg)	Range: 0 -> 2.0	(deg)	Range: -0.8 -> 0.6	(deg)

The tension leg shows very significant yaw motions in bigger sea states, and pitch angles are significant, especially for the extreme sea state, but also for the maximum operational state. The dominant yaw does apparently not occur according to the wave motion, but follows another time pattern, potentially influenced by the current direction.

The yaw movements are substantially attenuated with the restoring lines, which also bring some improvement for the pitch. The rigid extension frame does not bring visibly any further improvements, it does have the contrary effect on yaw. Regarding the pitch and roll values, the tension leg with restoring lines and extended frame seems to be the most stable. These observations confirm the two mooring solutions with restoring lines as most feasible options, which can also bring along added values for farm operation (see chapter 4).

3.4. Model validation

An important secondary use of the tank tests was to obtain experimental data for validating the existing models, as far as possible.

Major concern to this respect was the **pitch**-resonance frequency of the WEC and mooring assemblage in the water column, as previous simulations had indicated that for 70-100m water depth the Symphony type system could become problematic, as its natural pitch frequency approaches typical values of larger sea states, the numerical simulation of a corresponding configuration in WP2 of WETFEET (see [2]) resulted in a pitch resonance frequency at 10s. In the following Figure 26, the measured pitch response in the tank experiments for a regular wave of H = 2m is presented. The extended wire frame has small pitch amplitudes.

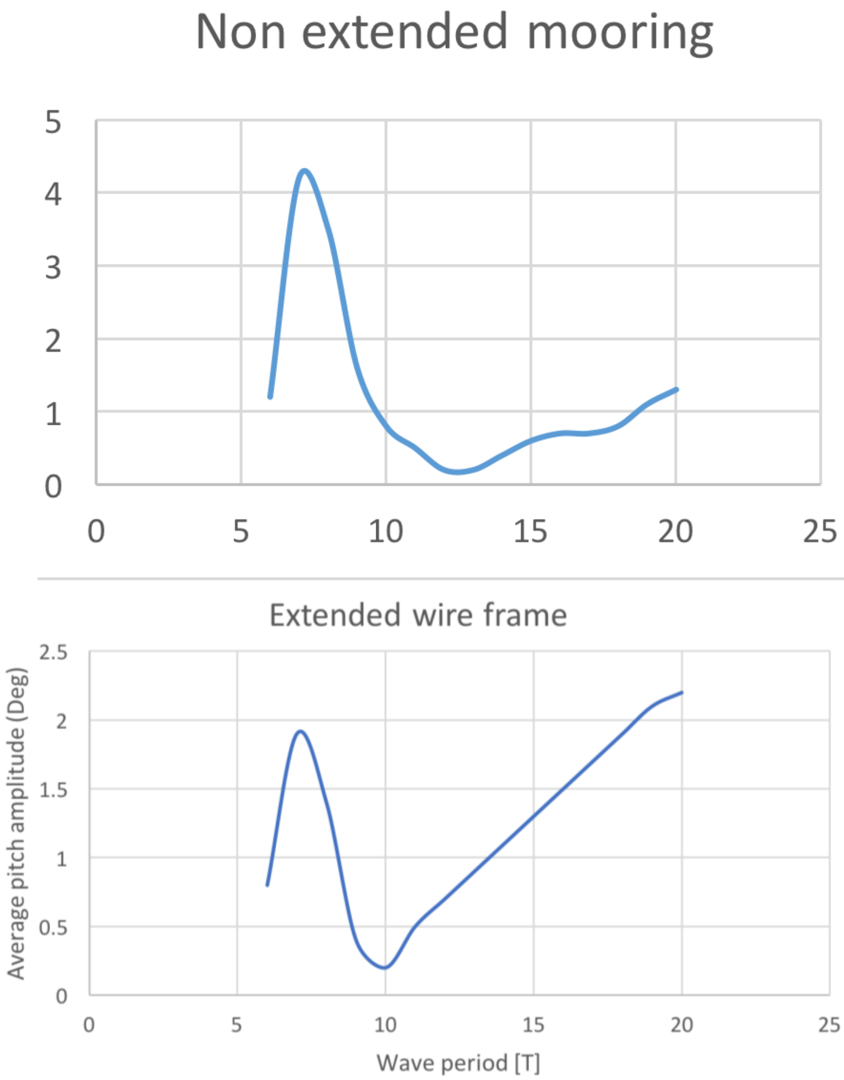


FIGURE 26: PITCH RESONANCE FREQUENCY GRAPHS OF THE TENSION LEG WITH RESTORING LINES, NON-EXTENDED (ABOVE) AND EXTENDED (BELOW). REGULAR WAVE H=2M. RESONANCE OCCURS AT 7S.

The tank test experiments show a distinct resonant peak for the pitch response of 7 seconds, both for the simple mooring, and for the extended wire frame. The deviation may be related to either a misalignment in the weight distribution of the model or other experimental inaccuracies, as well as model simplifications.

The steady and relatively steep linear increase for pitch response with increasing wave period between 10s and 20s does not show signs of being a second resonant peak, it is rather the expected increase due to increased wave length with the same response characteristics. Knowing that extreme sea states will have energy periods well beyond 10s, this circumstance gives confidence that the maximum wave-induced pitch angles of the Symphony WEC will remain within a predictable range, which is not expected to exceed 15-20 degrees (see Table 1).

The extended frame which allows the control cocoon to be removed, appears to be a promisingly stable solution, and preferable to the other options. However, there is further need of investigation into whether resonant movements may become a problem for this WEC-mooring configuration or not.

4. LARGE-SCALE IMPLEMENTATION ASPECTS

For large scale deployment, the 6m (or larger) diameter Symphony WECs could be installed as a stand-alone unit. When this is done, the total amount critical components inside the control cocoon cause the weight of the control cocoon to be dominant. A relatively heavy control cocoon gives minor profit in controllability.

When a wave farm of Symphony's is installed, a central control cocoon could be used in order to minimize the number of critical components in the control cocoon. This decreases the weight of the control cocoon, which makes the controllability of the cocoon better. Also, the O&M strategy could benefit, and the bundling of all critical functional equipment in a central cocoon might bring along significant CAPEX savings. An illustration of how such a system could be approached is shown in the following Figure 27 and Figure 28.

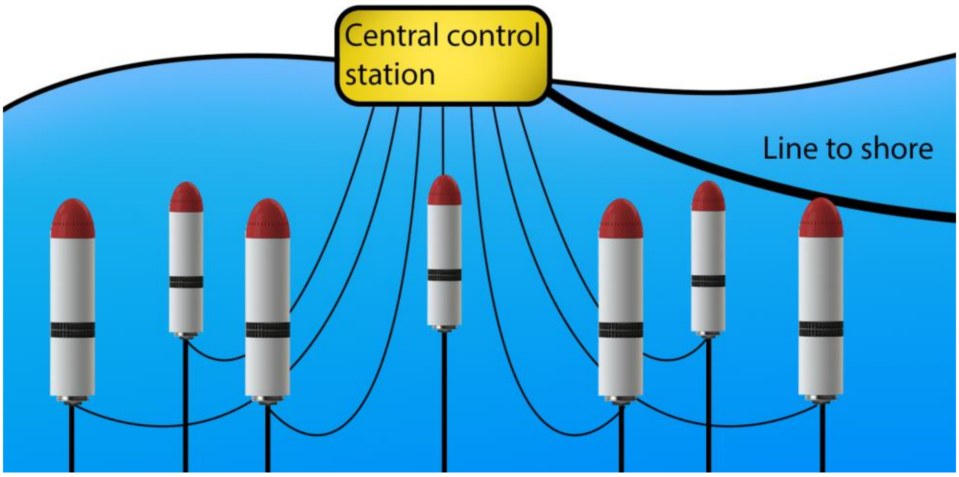


FIGURE 27: POTENTIAL CONFIGURATION FOR CONNECTION OF AN ARRAY OF SYMPHONY UNITS TO A CENTRAL CONTROL STATION; 'STAR' CONFIGURATION WITH FLOATING CENTRAL UNIT

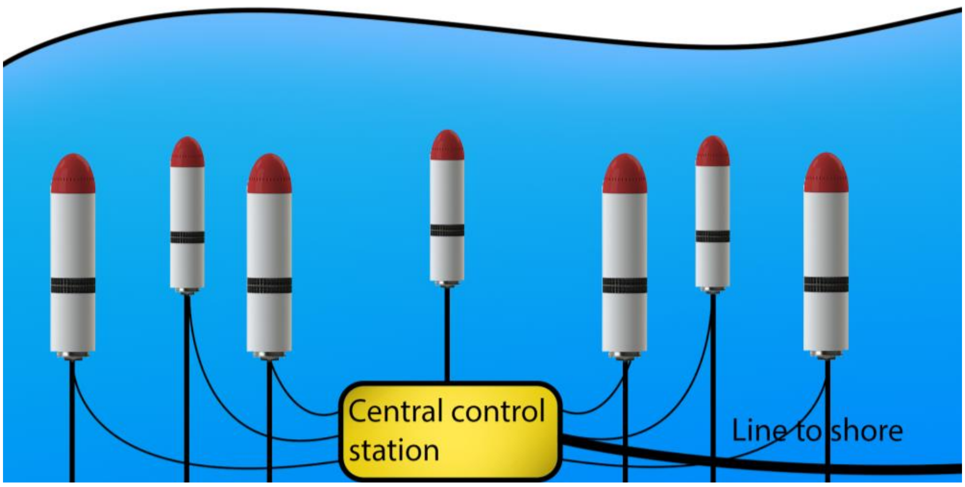


FIGURE 28: POTENTIAL CONFIGURATION FOR CONNECTION OF AN ARRAY OF SYMPHONY UNITS TO A CENTRAL CONTROL STATION; 'STAR' CONFIGURATION WITH SUBMERGED CENTRAL UNIT

In general, the vision of central control stations for Symphony technology includes not only power umbilical's as commonly designed for e.g. offshore wind farms, but umbilical's also including communication capacities and air supply. This requires relatively simple and off-the-shelf hose properties, has relatively low flow speed requirements and is not expected to cause critical dimensions with regards to drag and dynamic behavior. In addition, critical components of the control can be centralized in such a unit, reducing the critical components in each Symphony WEC.

In the first illustration in Figure 27, this is envisioned with a floating platform, which would provide access properties like current floating platforms, and could offer additional synergies as e.g. placing a wind turbine on top of the platform. The drawback of this solution might be the rather high costs of the platform and its moorings, due to its being fully exposed to extreme sea states.

Alternatively, the central control station could be a submerged station (see Figure 28), which is more in line with the Symphony design philosophy, where it is assumed that within a relatively short time frame, underwater robotics and therefore operation and maintenance options for fully submerged infrastructures and machinery will significantly advance. The use of submerged offshore substations for wave energy farms has been proposed in other projects, and technical solutions have been proposed, as e.g. by [3].

The main advantage of a submerged solution would be the station being protected from extreme wave action and floating debris. In addition, exposure to collisions is minimal, and the umbilical connections, both from WECs to the substation and from the substation to shore (or other farms), will be less subject to fatigue issues. The connections from the umbilical's to the WECs and the substation, as well as their position in the water column, make the design more straight-forward and reduces uncertainties due to being exposed to or close to very significant wave action.

Nevertheless, there is a significant need for further work on such concepts, and there are some specificities regarding the design for a Symphony farm that cannot be approached within the scope of the WETFFET project. At present, the additional technical challenges to fully submerged access are likely to weigh more than the drawbacks of a surface-piercing solution. However, once Symphony technology is at a stage of large array development, and WEC diameters of 6m or more are implemented, a submerged control station appears to be the most feasible solution.

5. Conclusions

The central objective of the present document is to analyze the feasibility of continuous submergence as part of the Symphony WEC concept. Due to this approach neither having any precedence nor significant field experience, several issues regarding the engineering of Symphony critical parts should be considered. The central approach for envisioning a 10-year (or longer) period of continuously submerged operation is to bundle the critical components for operation and safety into a separate, insulated unit removable from the WEC, the control cocoon. This is a result of one of very few available lessons learnt in the past. In addition to the structural cocoon design and preliminary choice of cocoon components and configuration inside the encapsulated volume, another aspect arising is if and how the WEC performs in terms of hydrodynamic behavior once the cocoon is removed. The cocoon represents approximately one third of the total weight of the Symphony WEC, thus the weight distribution is different. Pitch, roll and yaw movements of the WEC during operation, but also in heavy seas, are an essential factor for long-term survivability, and have been validated in tank experiments. The maximum movements both with and without cocoon indicated promising performance, and confirm the planned development path.

Also, the engineering of the cocoon structure, which is partly subject to high pressure differentials, does not appear to represent major obstacles. These calculations, preliminary design exercises regarding the choice of components and the tank tests suggest that using a control cocoon is feasible. The disadvantage of implementing a control cocoon is that the complexity of the wave energy device and the mooring increases. Using a control cocoon will most likely be only useful if the cocoon is significantly smaller than the complete device.

Related to submergence for large scale deployment, additional improvements for Symphony WEC design can be achieved if parts of the components housed inside the control cocoon are outsourced into a central control station. The main advantage of this approach is that weight can be reduced in each WEC, having direct impact on CAPEX. It further allows the use of smaller maintenance vessels, positively affecting OPEX.

The preliminary findings in this report strongly suggest further development work on the cocoon, with respect to large-scale array deployments and its potential configurations for central cocoon stations.

BIBLIOGRAPHY

[1] Prado, M.G.S., Neumann, F., Damen, M.E.C. and Gardner, F., 'AWS Results of Pilot Plant Testing ',6th EWTEC Glasgow 2005

[2] Teamwork Technology, 'Engineering challenges related to full scale and large deployment implementation of the proposed breakthroughs', EU-H2020 project WETFEET, Deliverable 2.3, Grant Agreement Nr. 646436, 2016

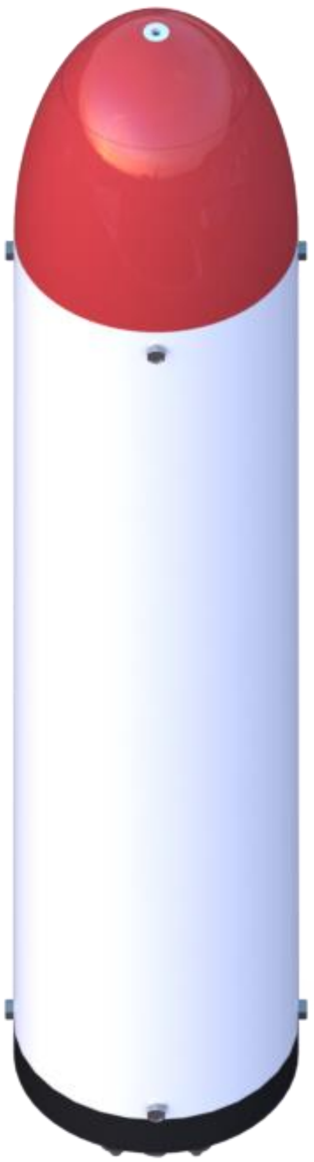
[3] Rahm, M., 'Ocean Wave Energy – Underwater Substation System for Wave Energy Converters', ISBN 978-91-554-7713-4, Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology 711, 2010

APPENDIX I - Tank test model setup

1. Description of the tank test model

The Symphony tank test model has a removable inner mass component which allows adjusting the hydrodynamic behaviour. This replicates the effect of removing the control cocoon of the Symphony wave energy converter. For simplified scaling and building of the model a tank test scale of 1 to 37.5 has been chosen. An illustration of the model is shown in the image below.

Dimensions



General information of the tank test model

Subject	**Real scale**	**Tank test scale**	**unit**
Scale	1	37.5	[-]
Height	29000	733	[mm]
Diameter	6000	160	[mm]
Volume	697826	13.23	[l]

Dimensions

	Middle position (Inn)		Bottom position (new)		
Diameter	160	[mm]	Diameter	160	[mm]
Height	666,667	[mm]	Height	666,667	[mm]
Volume	12,3318	[l]	Volume	10,396	[l]
Mass	9,692183	[kg]	Mass	9,59501054	[kg]
Excess buoyancy	2,639617	[l]	Excess buoyancy	0,80098946	[l]
Exterior			**Exterior**		
Mass dome	1,000	[kg]	Mass dome	1,000	[kg]
Mass PVC pipe	1,000	[kg]	Mass PVC pipe	1,000	[kg]
Mass bottom cap	0,500	[kg]	Mass bottom cap	0,500	[kg]
Total	2,5000	[kg]	Total	2,5000	[kg]
Interior			**Interior**		
Rod	0,500	[kg]	Rod	0,500	[kg]
Weight discs	6,6922	[kg]	Weight discs	6,5950	[kg]
Weight per disc		[kg]	Weight per disc		[kg]
Number of discs		[kg]	Number of discs		[kg]
Centres	*[from top]*		**Centres**	*[from top]*	
Semi stable			*Semi stable*		
CB	-359	[mm]	CB	-311	[mm]
CM	-480	[mm]	CM	-420	[mm]
Stable	*[1m] lowered (real scale)*		*Stable*	*[1m] lowered (real scale)*	
CB	-359	[mm]	CB	-311	[mm]
CM	-506,67	[mm]	CM	-446,66667	[mm]

The following sea states were performed:

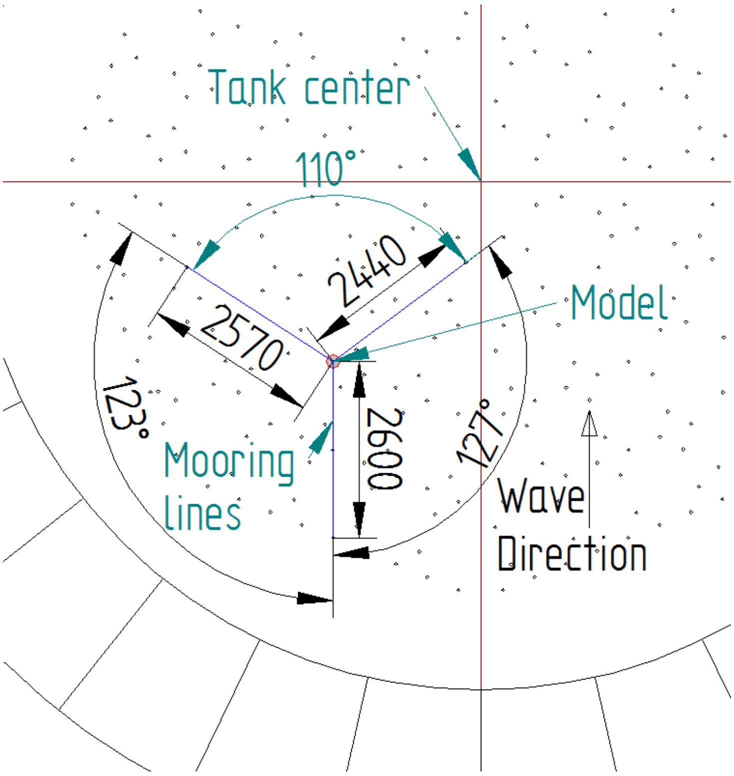
H_s = 2m / T_e = 10s. Each test has been performed for 1 hour (scaled to real sea-state)

H_s = 5m / T_e = 12s. Each test has been performed for 1 hour (scaled to real sea-state)

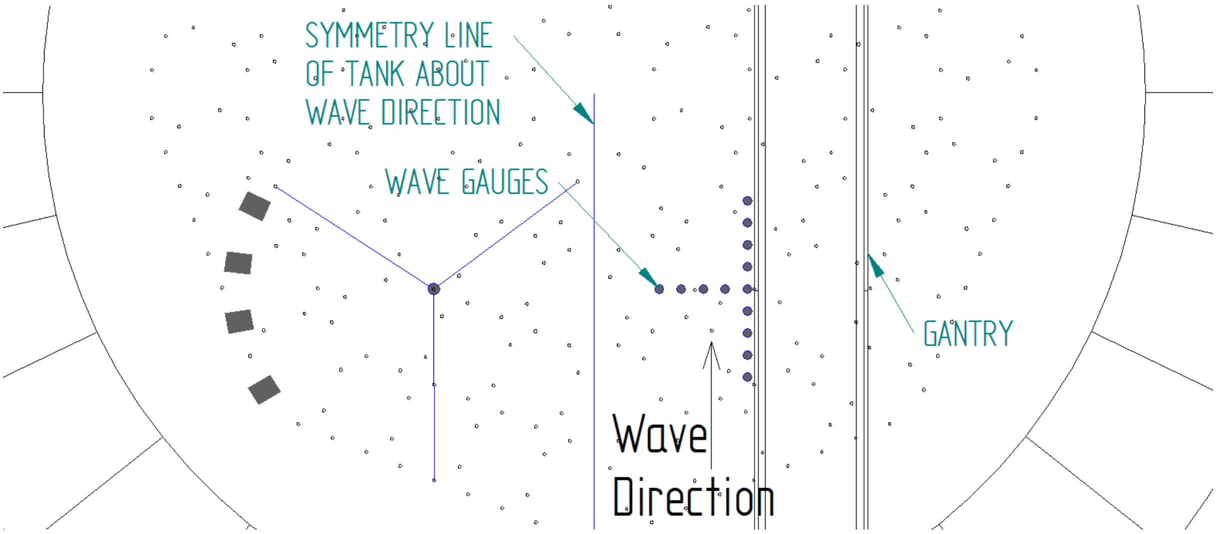
H_s = 11m / T_e = 13s. Each test has been performed for 2 hours (scaled to real sea-state)

H_s = 11m was the maximum sea state that the tank could generate at the chosen scale.

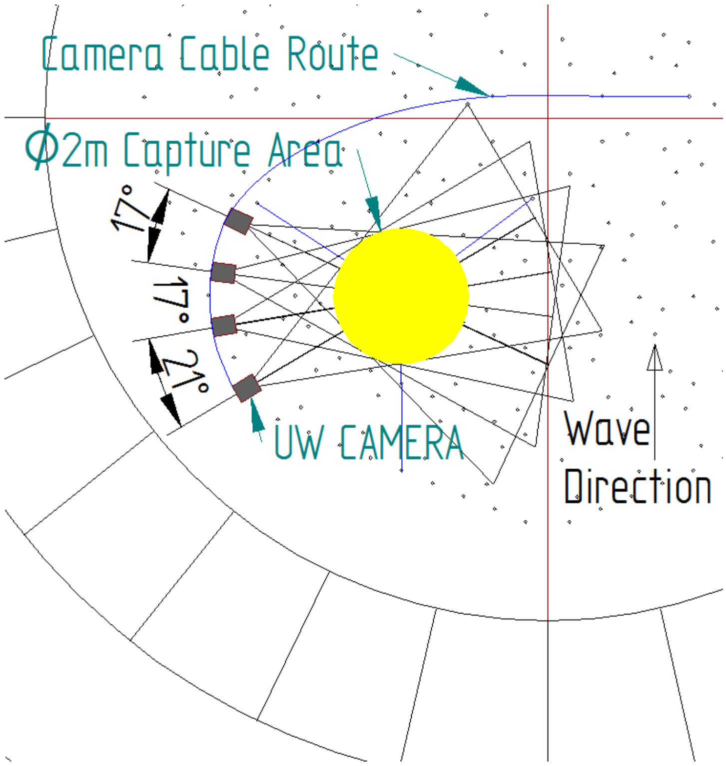
Mooring dimensions

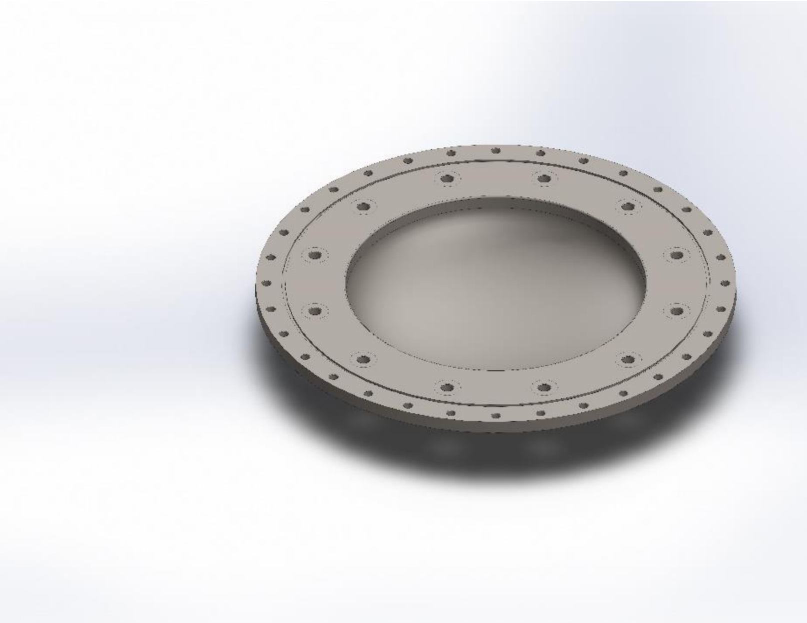


Wave Gauge Setup



Camera layout





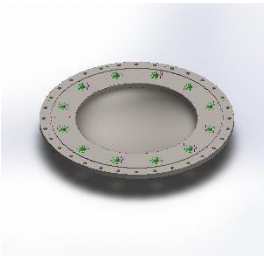
FEM Analysis of the cocoon bottom plate

Designer: Hans van Noorloos

Study name: Static 1

Analysis type: Static

Model Information

Model name: Bottom plate BIG; Current Configuration: Default		
Solid Bodies		
Document Name and Reference	Treated As	Volumetric Properties
Scale1 	Solid Body	Mass:31324 kg Volume: 3.98596 m^3 Density: 7858.59 kg/m^3 Weight: 306976 N

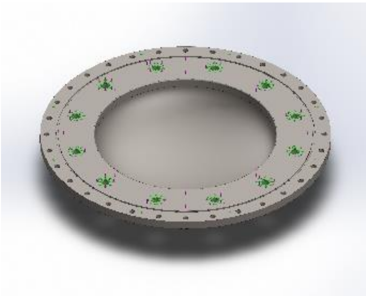
Study Properties

Study name	Static 1
Analysis type	Static
Mesh type	Solid Mesh
Thermal Effect:	On
Thermal option	Include temperature loads
Zero strain temperature	298 Kelvin
Include fluid pressure effects from SOLIDWORKS Flow Simulation	Off
Solver type	FFEPlus
Inplane Effect:	Off
Soft Spring:	Off
Inertial Relief:	Off
Incompatible bonding options	Automatic
Large displacement	Off
Compute free body forces	On
Friction	Off
Use Adaptive Method:	Off
Result folder	SOLIDWORKS document (C:\Users\Hans\Desktop\Symphony\Calculations)

Units

Unit system:	SI (MKS)
Length/Displacement	mm
Temperature	Kelvin
Angular velocity	Rad/sec
Pressure/Stress	N/m^2

Material Properties

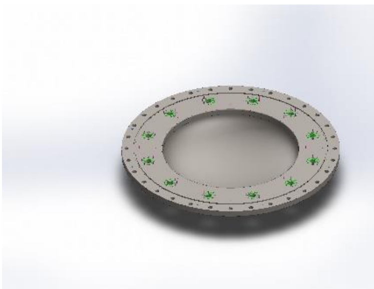
Model Reference	Properties	Components
	Name: **1023 Carbon Steel Sheet (SS)** Model type: **Linear Elastic Isotropic** Default failure criterion: **Unknown** Yield strength: **2.82685e+008 N/m^2** Tensile strength: **4.25e+008 N/m^2** Elastic modulus: **2.05e+011 N/m^2** Poisson's ratio: **0.29** Mass density: **7858 kg/m^3** Shear modulus: **8e+010 N/m^2** Thermal expansion coefficient: **1.2e-005 /Kelvin**	**SolidBody 1 (Scale1) (Bottom wplate BIG)**
Curve Data:N/A		

Loads and Fixtures

Fixture name	Fixture Image	Fixture Details
Guidance rods		**Entities:** **24 face(s)** **Type:** **Fixed Geometry**

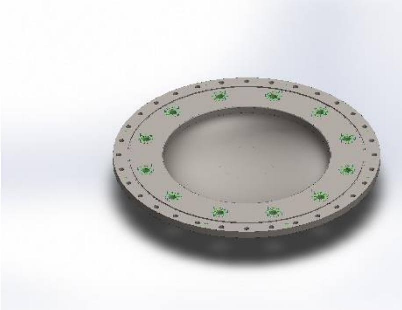
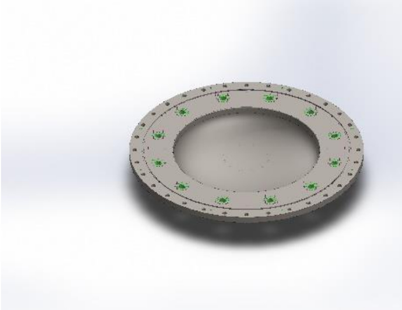
Resultant Forces

Components	X	Y	Z	Resultant
Reaction force(N)	**-5056.46**	**2.67407e+007**	**4839.13**	**2.67407e+007**
Reaction Moment(N.m)	**0**	**0**	**0**	**0**

Fixture name	Fixture Image	Fixture Details
Outer flange connection		**Entities:** **1 face(s)** **Type:** **Fixed Geometry**

Resultant Forces

Components	X	Y	Z	Resultant
Reaction force(N)	**5097.91**	**5.99168e+006**	**-4867.33**	**5.99168e+006**
Reaction Moment(N.m)	**0**	**0**	**0**	**0**

Load name	Load Image	Load Details
Cocoon pressure		**Entities:** 1 face(s) **Type:** Apply normal force **Value:** 4e+007 N
Hydrostatic pressure		**Entities:** 3 face(s) **Type:** Normal to selected face **Value:** 300000 **Units:** N/m^2 **Phase Angle:** 0 **Units:** deg

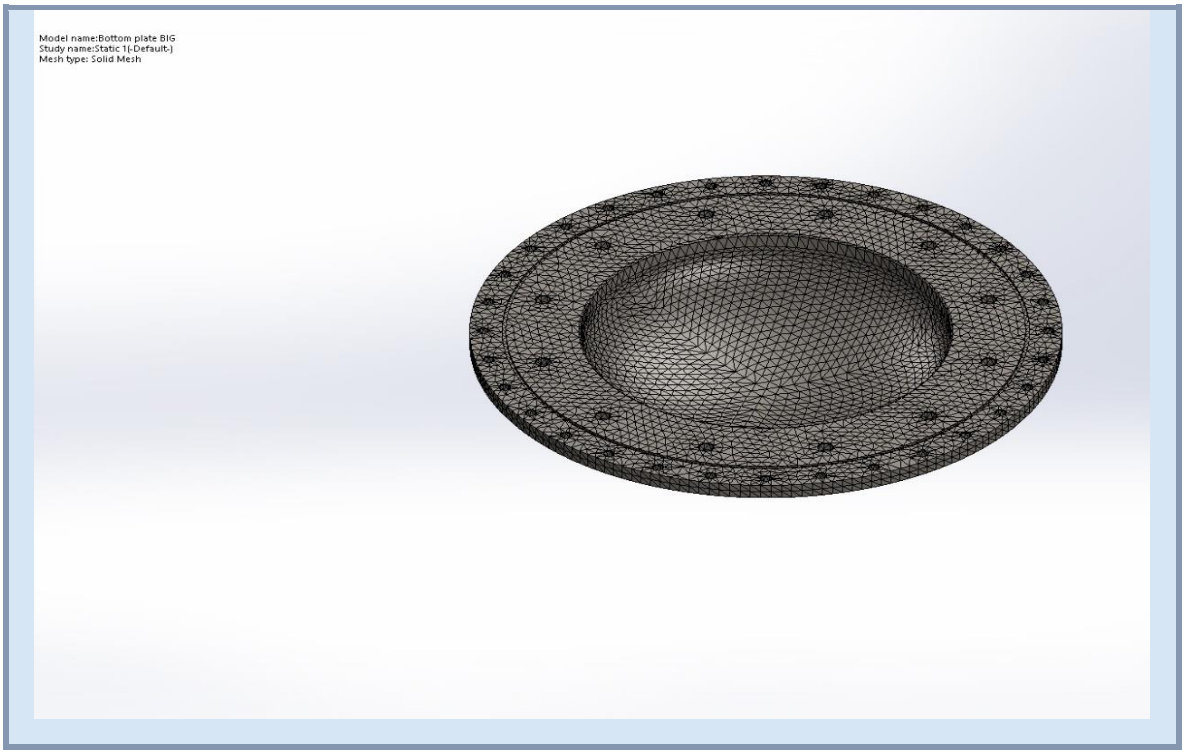
WETFEET

Mesh information

Mesh type	Solid Mesh
Mesher Used:	Standard mesh
Automatic Transition:	Off
Include Mesh Auto Loops:	Off
Jacobian points	4 Points
Element Size	99.7508 mm
Tolerance	4.98754 mm
Mesh Quality Plot	High

Mesh information - Details

Total Nodes	84209
Total Elements	48960
Maximum Aspect Ratio	16.815
% of elements with Aspect Ratio < 3	85.7
% of elements with Aspect Ratio > 10	0.112
% of distorted elements(Jacobian)	0
Time to complete mesh(hh;mm;ss):	00:00:08
Computer name:	



Resultant Forces

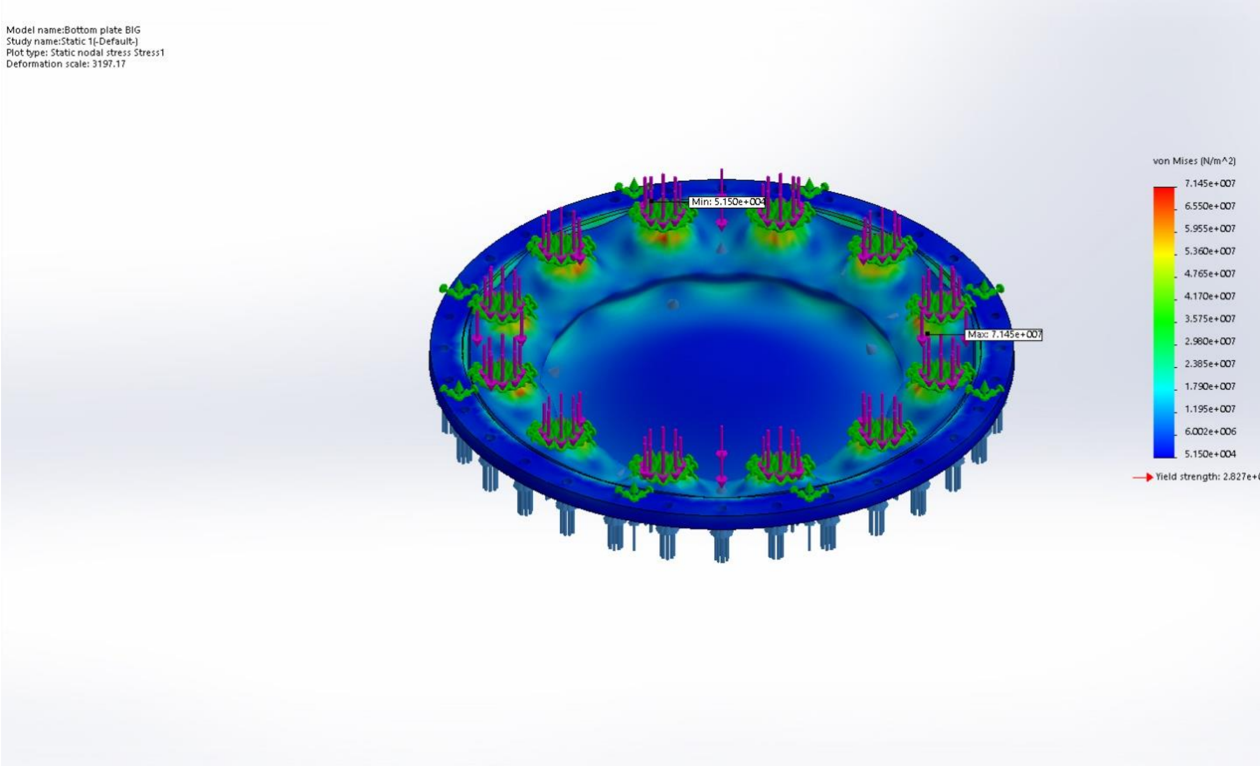
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	41.1161	3.27324e+007	-27.7359	3.27324e+007

Reaction Moments

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0	0	0	0

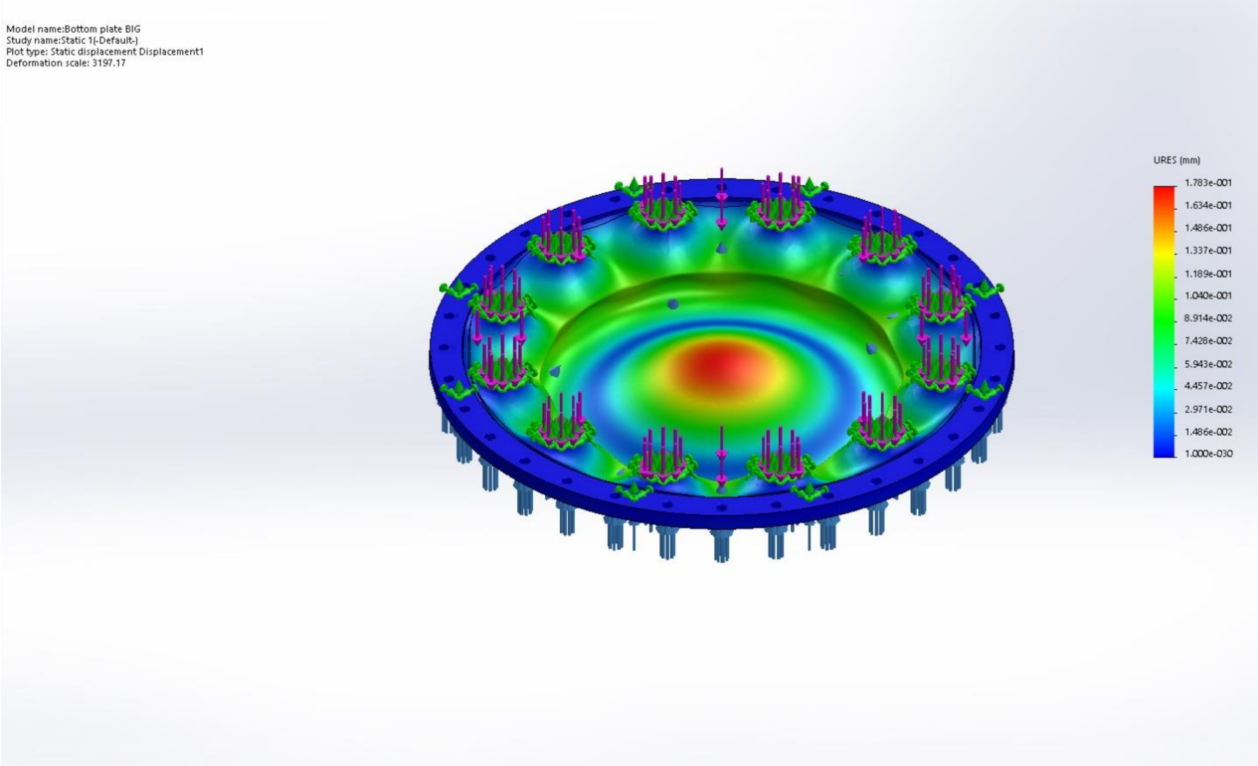
Study Results

Name	Type	Min	Max
Stress1	VON: von Mises Stress	5.150e+004N/m^2 Node: 57557	7.145e+007N/m^2 Node: 50762



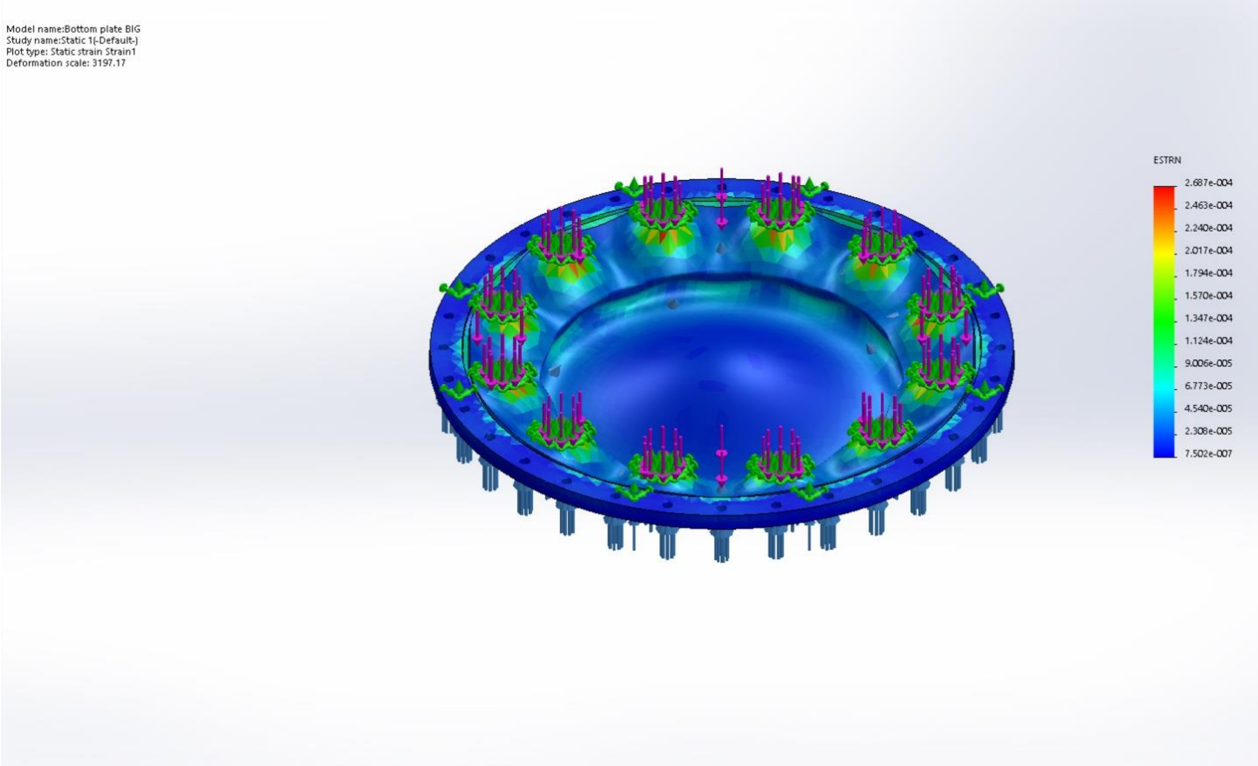
Bottom plate BIG-Static 1-Stress-Stress1

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0.000e+000mm Node: 2875	1.783e-001mm Node: 1134



Bottom plate BIG-Static 1-Displacement-Displacement1

Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	7.502e-007 Element: 34265	2.687e-004 Element: 47900



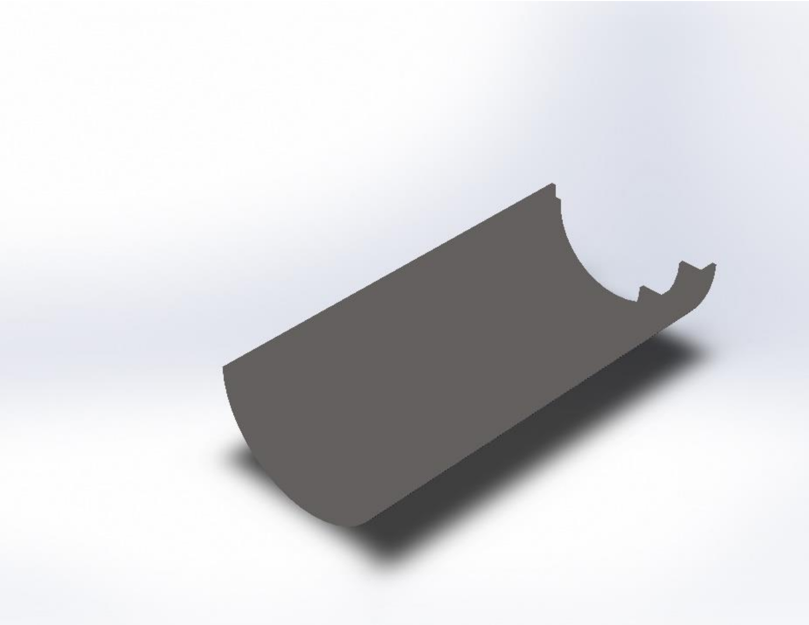
Bottom plate BIG-Static 1-Strain-Strain1

Final remarks

The maximum occurring stress is 70 Mpa. This is 4 times lower than the Yield strength of the chosen material (Carbon steel AISI 1023). The maximum displacement is 0.2mm. Safety factors are in excess of 3-4.

Name	Type	Min	Max
Factor of Safety1	Automatic	3.956e+000 Node: 50762	5.490e+003 Node: 57557

Bottom plate BIG-Static 1-Factor of Safety-Factor of Safety1



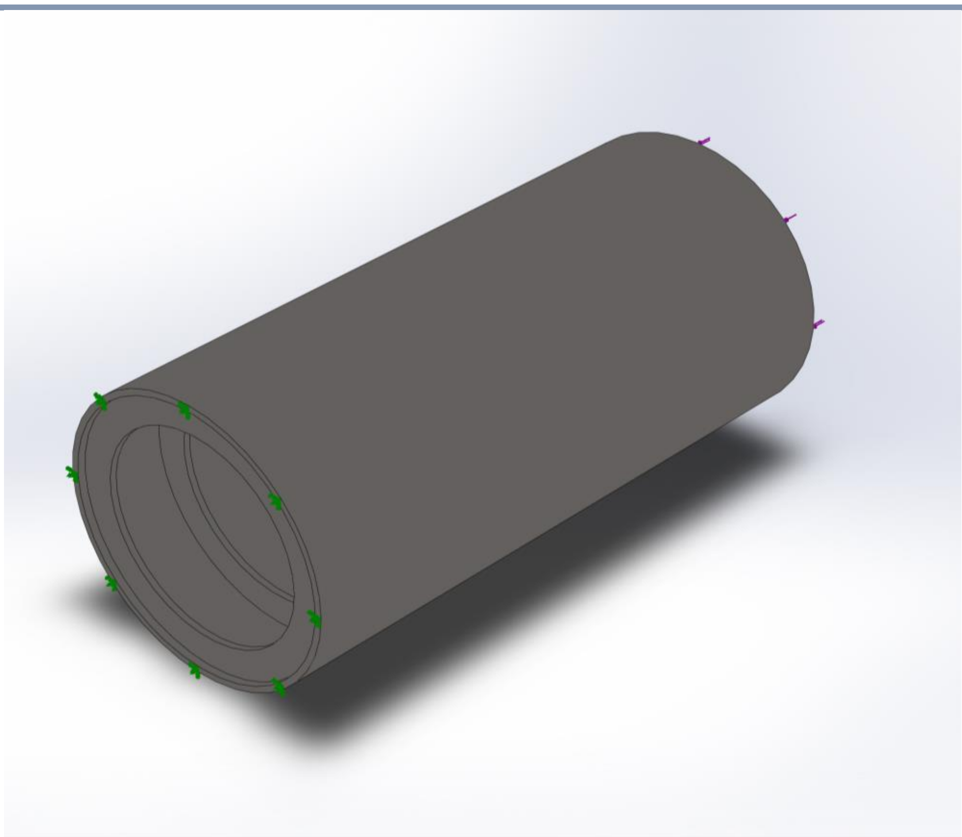
FEM analysis of Symphony 6m cocoon hull

Designer: Hans van Noorloos

Study name: Static 1

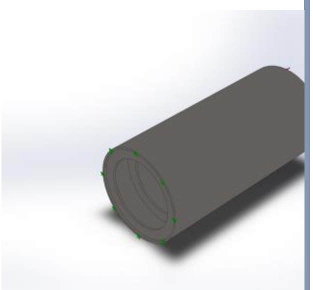
Analysis type: Static

Model Information



Model name: Cocoon lower cylinder big semi simplified

Current Configuration: Default

Solid Bodies			
Document Name and Reference	Treated As	Volumetric Properties	Document Path/Date Modified
Scale2 	Solid Body	Mass:68961.7 kg Volume:8.84125 m^3 Density:7800 kg/m^3 Weight:675825 N	

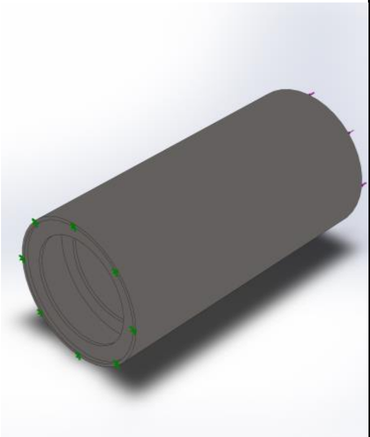
Study Properties

Study name	Static 1
Analysis type	Static
Mesh type	Solid Mesh
Thermal Effect:	On
Thermal option	Include temperature loads
Zero strain temperature	298 Kelvin
Include fluid pressure effects from SOLIDWORKS Flow Simulation	Off
Solver type	FFEPlus
Inplane Effect:	Off
Soft Spring:	Off
Inertial Relief:	Off
Incompatible bonding options	Automatic
Large displacement	Off
Compute free body forces	On
Friction	Off
Use Adaptive Method:	Off
Result folder	SOLIDWORKS document (C:\Users\Hans\Desktop\Symphony\Calculations)

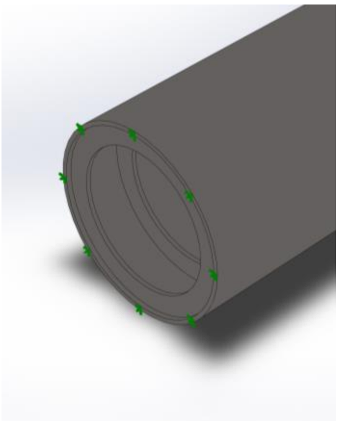
Units

Unit system:	SI (MKS)
Length/Displacement	mm
Temperature	Kelvin
Angular velocity	Rad/sec
Pressure/Stress	N/m^2

Material Properties

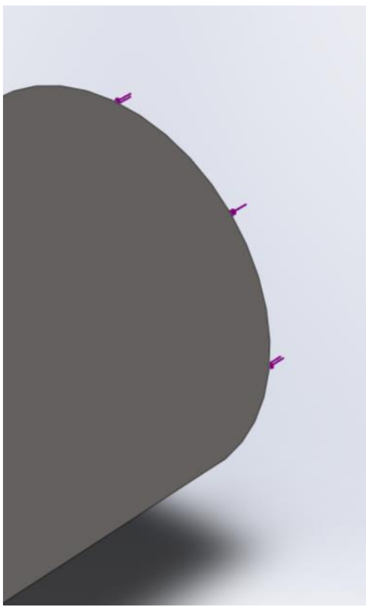
Model Reference	Properties		Components
	Name:	**Plain Carbon Steel**	
	Model type:	**Linear Elastic Isotropic**	
	Default failure criterion:	**Max von Mises Stress**	
	Yield strength:	**2.20594e+008 N/m^2**	
	Tensile strength:	**3.99826e+008 N/m^2**	
	Elastic modulus:	**2.1e+011 N/m^2**	
	Poisson's ratio:	**0.28**	
	Mass density:	**7800 kg/m^3**	
	Shear modulus:	**7.9e+010 N/m^2**	
	Thermal expansion coefficient:	**1.3e-005 /Kelvin**	
Curve Data:N/A			

Loads and Fixtures

Fixture name	Fixture Image	Fixture Details
Fixation		**Entities:** **1 face(s)** **Type:** **Fixed Geometry**

Resultant Forces

Components	X	Y	Z	Resultant
Reaction force(N)	**-41.5723**	**69.9219**	**-4.00001e+007**	**4.00001e+007**
Reaction Moment(N.m)	**0**	**0**	**0**	**0**

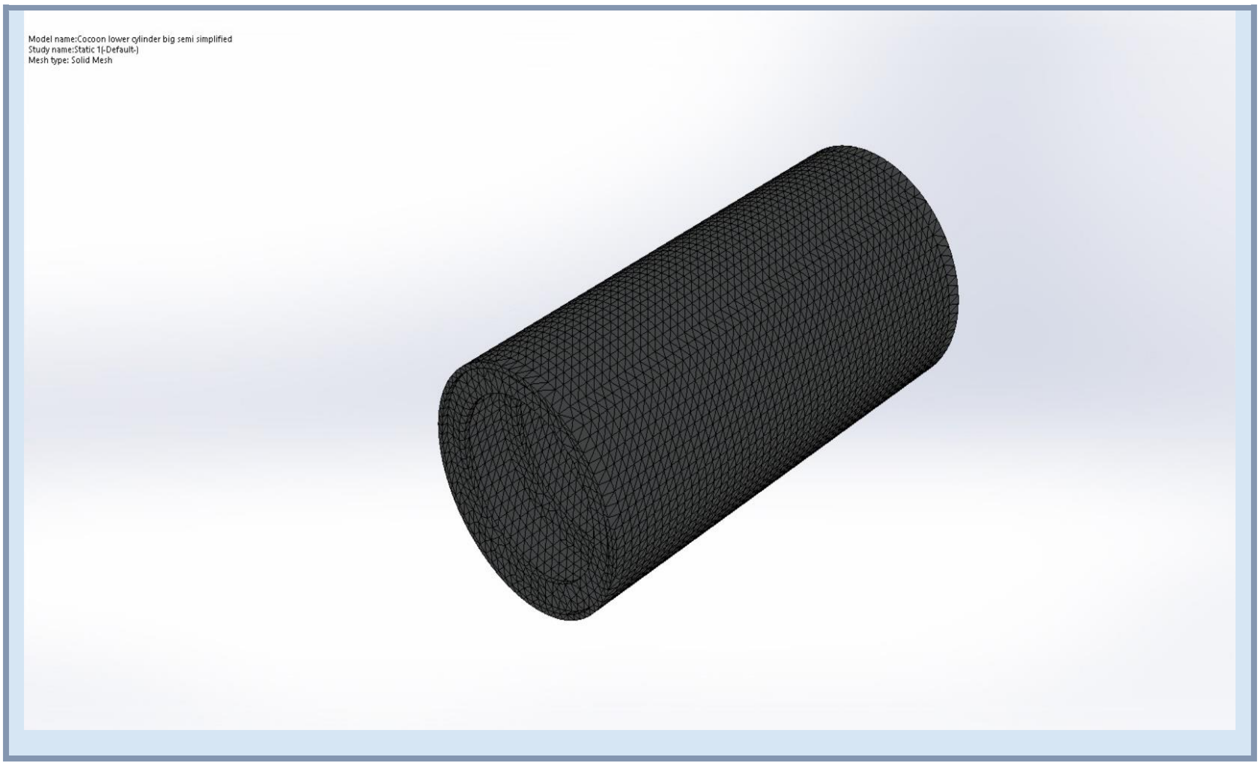
Load name	Load Image	Load Details
Pressure from spring tank		**Entities:** **1 face(s)** **Type:** **Apply normal force** **Value:** **4e+007 N**

Mesh information

Mesh type	Solid Mesh
Mesher Used:	Standard mesh
Automatic Transition:	Off
Include Mesh Auto Loops:	Off
Jacobian points	4 Points
Element Size	148.746 mm
Tolerance	7.43728 mm
Mesh Quality Plot	High

Mesh information - Details

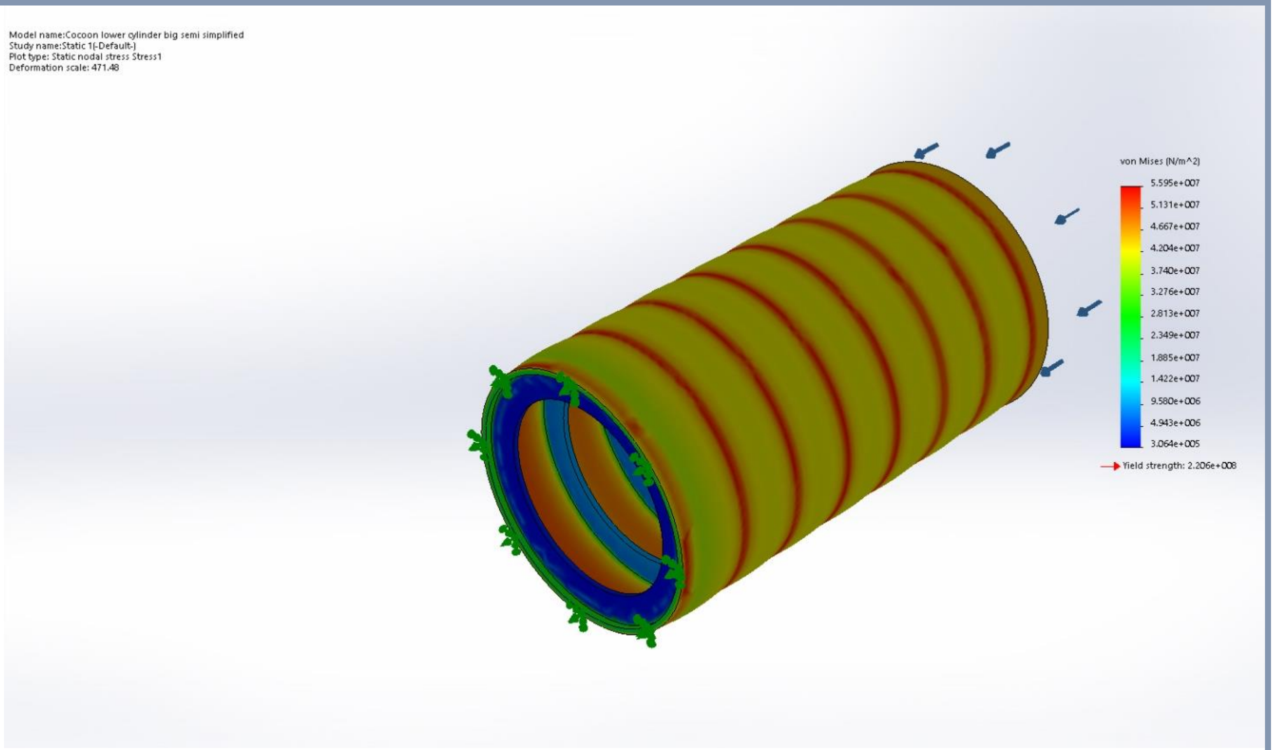
Total Nodes	63629
Total Elements	31960
Maximum Aspect Ratio	5.7795
% of elements with Aspect Ratio < 3	98.1
% of elements with Aspect Ratio > 10	0
% of distorted elements(Jacobian)	0
Time to complete mesh(hh;mm;ss):	00:00:05
Computer name:	


Model name:Cocoon lower cylinder big semi simplified
Study name:Static 1(-Default-)
Mesh type: Solid Mesh

WETFEET

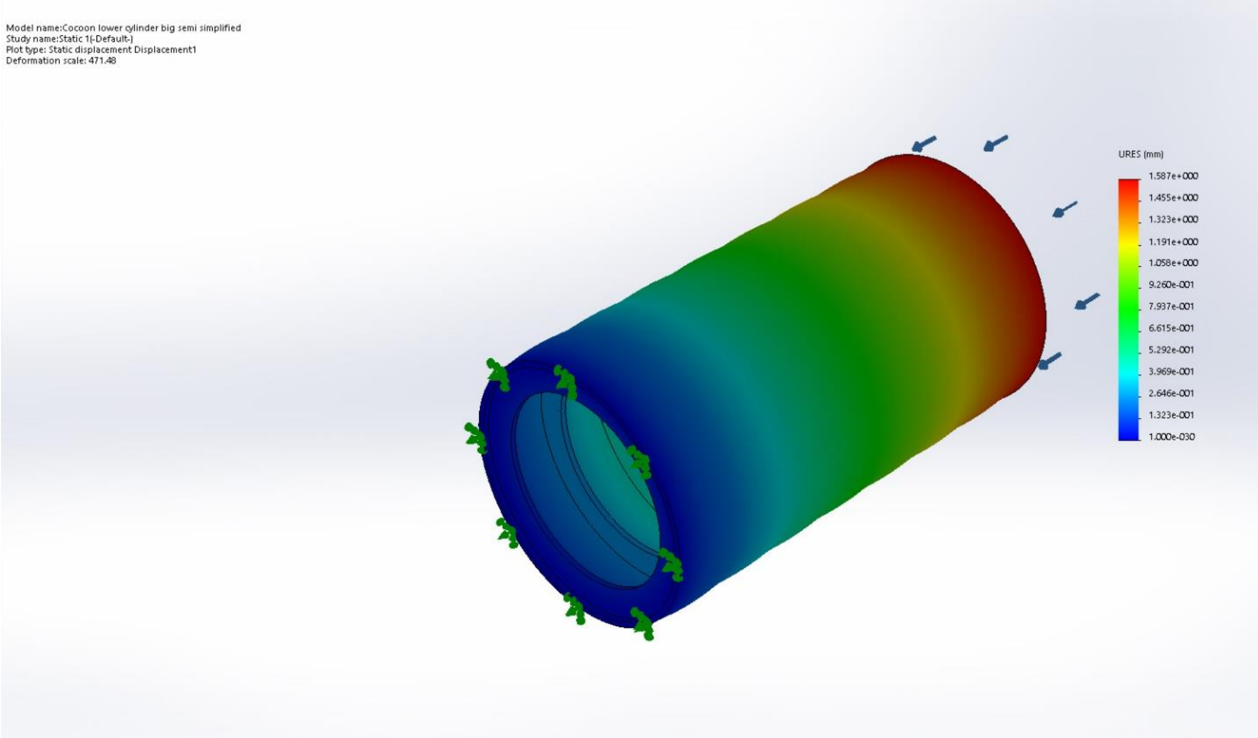
Study Results

Name	Type	Min	Max
Stress1	VON: von Mises Stress	3.064e+005N/m^2 Node: 10951	5.595e+007N/m^2 Node: 686



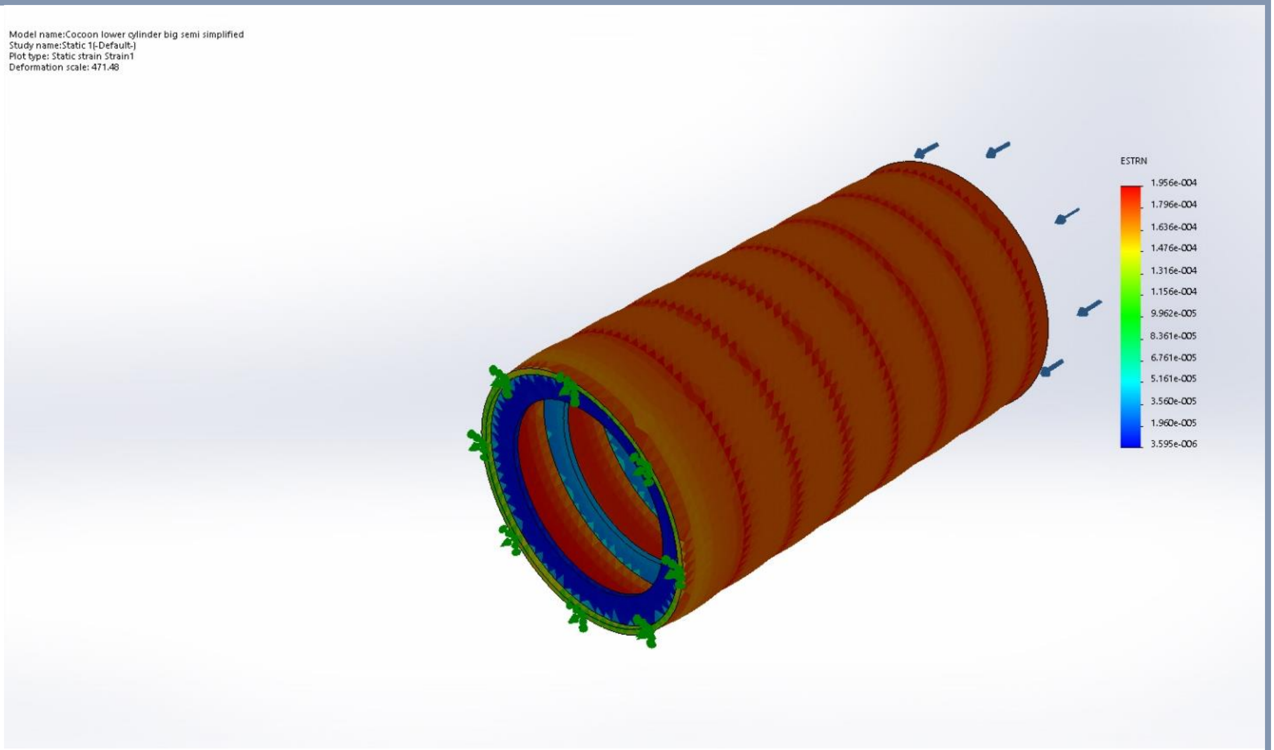
Cocoon lower cylinder big semi simplified-Static 1-Stress-Stress1

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0.000e+000mm Node: 625	1.587e+000mm Node: 50744



Cocoon lower cylinder big semi simplified-Static 1-Displacement-Displacement1

Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	3.595e-006 Element: 28109	1.956e-004 Element: 25917



Cocoon lower cylinder big semi simplified-Static 1-Strain-Strain1

Final remarks

The maximum occurring stress is 60 Mpa. This is over 4 times lower than the yield strength of the chosen material (Carbon steel AISI 1023). The maximum displacement is 1.6mm.

APPENDIX IV - Turbine specifications

Technical Note: SY_PTO-2016-1

PTO turbine design input for the 1.5[m] prototype

Jarno de Jong, Hans van Noorloos

Subject	Specifications of the PTO design values of the 1.5[m] prototype
Abstract	This report is a specification report of the PTO turbine of the Symphony Wave Power 1,5[m] prototype. The most important input values for the design of the PTO turbine are stated, as well as a small description from where these values are derived.

Revisions			
Revision	Name	Date	Approved
0.1	Jarno de Jong	14-01-2016	
1.0	Hans van Noorloos	14-03-2016	
1.1	Hans van Noorloos	07-07-2016	

Introduction

This report is a specification document for the power take-off turbine for the Symphony Wave Power 1,5[m] prototype. This document states the flow and pressures which the turbine should be able to handle during its lifetime. A proposal for the final dimensions of the turbine will be based upon the information in this document by Wolters Engineering.

Specifications

Pressures

The neutral pressure is a set value. The pressure amplitude follows from the loading and unloading of the air spring in the air spring chamber. This value does not depend on the wave force acting on the Symphony. However, it might happen that a large wave pushes the Symphony into the braking system which changes the pressure more than for a full stroke. The Symphony makes 4 million cycles per year, but the maximum pressure amplitude including the brakes only occurs incidentally.

If there is enough energy available in the Symphony to start extracting energy from the system, the PTO will start to create a pressure difference over the turbine. This pressure difference over the turbine is dependent of the amplitude of the wave acting on the Symphony,

$$\Delta p_{PTO} = a_{wave} * \rho * g * f_d * f_m$$

where

$$f_m = \frac{\pi * r_{Sym}^2 * stroke * 2}{q}$$

$$f_d = 0.7$$

This leads to a Δp_{PTO} of approximately 4.9 bar.

The pressure difference between the turbine house and the pressure in the technical cocoon acts on the bottom plate of the turbine casing. The pressure in the cocoon is 1 bar.

Neutral pressure	15 bar
Pressure amplitude for max stroke (excl. brake)	+3.44 / -3.04 bar
Pressure amplitude for max stroke (incl. brake)	+6.17 / -4.1 bar
Max pressure drop over turbine	4.9 bar
Pressure difference between turbine house and technical cocoon.	14 bar (+6.17 / -4.1)

Fatigue cycles turbine blades

The Symphony makes 4 million cycles a year. This means that the turbine changes direction of rotation 4 million times per year. The pressure drop over the turbine (which acts on the turbine blades) is different for every wave height. The pressure difference and occurrence (in %) is stated in the table below.

Amplitude	0,25	0,5	0,75	1	1,25	1,5	1,75	2	2,25	2,5
pressure drop [bar]	0,24	0,49	0,73	0,97	1,21	1,46	1,70	1,94	2,18	2,43
Torque on Runner[N*m]	45,85	93,6	139,5	185,3	231,2	278,9	324,8	370,6	416,5	464,2
Occurrence	15,80%	29,60%	21,69%	12,90%	7,45%	4,41%	2,69%	1,70%	1,09%	0,71%

Amplitude	2,75	3	3,25	3,5	3,75	4	4,25	4,5	4,75	5
pressure drop [bar]	2,67	2,91	3,16	3,40	3,64	3,88	4,13	4,37	4,61	4,85
Torque on Runner[N*m]	510,1	555,9	603,7	649,5	695,4	741,2	789,0	834,8	880,7	926,5
Occurrence	0,47%	0,31%	0,20%	0,13%	0,09%	0,06%	0,04%	0,03%	0,02%	0,01%

Flow and velocities

The total water displacement in one stroke (up and down, no brakes) is 0.5 m³. The peak flow for a 10 second wave is:

$$Q_{max} = \frac{500\ l}{10} * \frac{\pi}{2}$$

The term π/2 follows from the ratio between the average value and maximum value of a sine function. An angular velocity of 350 RPM is required for efficient energy conversion in the generator.

Total water displacement in 1 cycle	0.5 m³
Peak flow for one cycle [10s]	79 l/s
Rotations per minute at peak flow [10s]	350 RPM

Fatigue data of rotational speed

The Symphony makes 4 million cycles a year. This means that the turbine changes direction of rotation 4 million times per year. The rotational speed of the runners depends on the wave period time. The rotational speed of the runners and occurrence (in % and amounts per year) is stated in the table below.

Cycle time	4-	5	6	7	8	9	10	11	12	13
Rotational speed[RPM]	875+	700	583.3	500	437.5	388.9	350	318.2	291.7	269.2
Occurrence [%]	<0.1%	0.1%	9.2%	23.4%	21.1%	18.6%	14.1%	8.3%	3.7%	1.1%
Occurrence [n/year]	<100	4152	369563	937610	843351	745770	564310	330530	146579	44846

Cycle time	14	15	16	17	18	19	20	21	22	22+
Rotational speed[RPM]	250	233.3	218.8	205.9	194.4	184.2	175	166.7	159.1	159.1-
Occurrence [%]	0.3%	0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%
Occurrence [n/year]	12457	830	<100	<100	<100	<100	<100	<100	<100	<100

Worst case situation

In the worst case situation looking at speeds and flows occurs when the generator is disconnected. The total water displacement in one stroke including brakes is 1 m^3. For the worst case situation a 5 second cycle time is used.

$$Q_{max} = \frac{1000\, l}{5} * \frac{\pi}{2}$$

The term π/2 follows from the ratio between the average value and maximum value of a sine function.

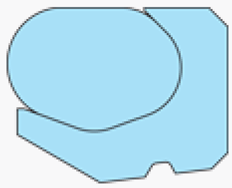
Total water displacement in 1 cycle	1.2 m^3
Peak flow for one cycle [4s]	314 l/s
Rotations per minute at peak flow [10s]	1400 RPM

APPENDIX V - Dynamic seal details

Potential off-the-shelf models for each required item are shown in the following.

Primary seal

(Source: http://www.tss.trelleborg.com/apps/ros/views/sealDetail.action?id=173)

Seal subtype details	
Seal image	
Seal family	Roto VL Seal®
Seal type	Roto VL
Type description	Turcon® Roto VL Seal® is a single-acting rotary shaft seal with the same groove dimensions as standard O-Rings. The seal is used in hydraulics and general machine construction.
TSS code	TE1
Seal configuration	std
Seal function	S (Single-Acting)
Key to Application	
Type of Movement	(Reciprocating) (Rotary) (Oscillating) (Helix)
Materials Info	

Primary seal material	M15
Color	Dark grey *
Materials description short	PTFE, Polyaramid, mineral fibre, lubricant and graphite filled.
Materials description long	For lubricating fluid and “starved” lubrication. Excellent for rotary service. High sealing effect. Very good wear properties. Low friction. Good extrusion resistance
Preferred	Yes **
Suitable for Constant rotation	
Seal capabilities	
Size range	From 6.0 to 2600.0 mm
Max speed	4.0 m/s
Seal pressure limit	25.0 MPa
Max PV	5.0 MPa x m/s
Min and Max temp	Min :-45.0 Max: 200.0°C ***
Valid lubrication	GREASE , OIL
Installation Info	
Recommended Shaft Hardness	55 HRc

*Colour variations can occur.

**Yes, means that the combination of the seal type and material is considered as std, and is therefore recommended.

***The temperature refers to the dynamic material. Please make sure to select a suitable o-ring material for the temperature range and media.

Secondary seal

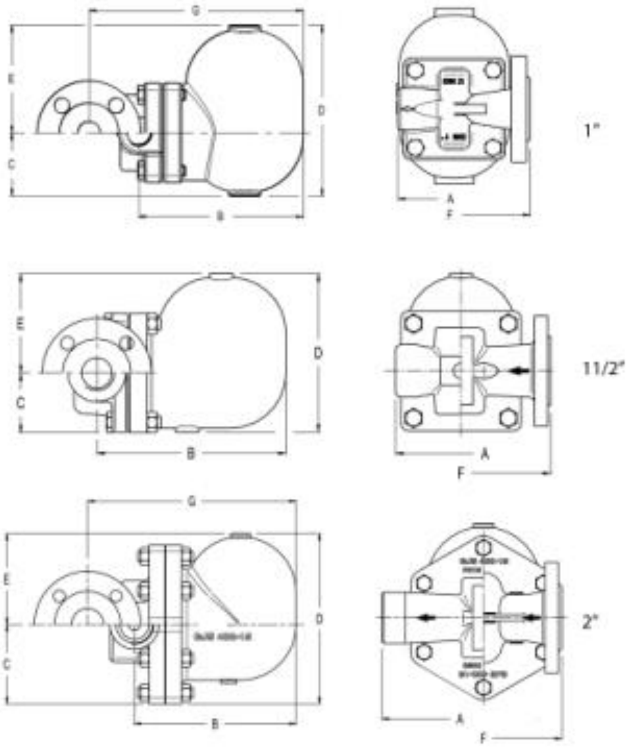
GARLOCK PS Lip Gylon® 200x220x1 (Source: https://shop.eriks.nl/ProductDisplay?storeId=100001&urlLangId=-1&urlLangId=31&productId=689041&urlRequestType=Base&categoryId=22538&langId=-1&catalogId=1000 → ERIKS item #: 100136869)

Product features:

Attribute	Value
Internal diameter (mm)	200
Outer diameter (mm)	220
Thickness (mm)	1
Material	PTFE
Colour	Black
Externally sealing	No

Floating steam trap

ECON Steam trap ECON 873E DCI 14b 1" (Source: https://shop.eriks.nl/en/valves-steam-traps-float-controlled-steam-traps-with-threaded-connection/condenspot-econ-873e-ggg-14b-1-quot-



12714936/)

Product features:

Attribute	Value
Material	Nodular cast iron
Nominal inner diameter	1" (25)
Article compression stage	PN 16
Max. pressure difference (bar)	14
Connections	Internal thread (BSPP)
Figure number ERIKS group	873E
Material quality	EN-JS1030
With automatic de-aerator	Yes
For horizontal installation	Yes
For vertical installation	No
Material cover	EN-JS1030
Material insert	1.4301
Material, packing 1	Graphite
Seat material	1.4006
Material disc	1.4125

APPENDIX VI - Generator & Controls

THE SWITCH

Medium-speed permanent magnet generators | PMG 1650 – 6400 kW

PMG 1650 – 6400 kW

136 – 414 rpm

100% purpose-built for wind

The Switch is fully committed to wind power generation. With our purpose-built permanent magnet generators (PMG), we cover all wind power applications. Each PMG is designed with special magnet shapes and arrangements to match specific wind conditions for smooth operation and maximum efficiency.

The Switch PMGs provide excellent availability and productivity. By eliminating cogging, we have reduced the overall mechanical stress. This improves reliability and extends the turbine's lifetime.

The Switch medium-speed PMGs typically feature a single- or two-stage gearbox and have a much higher annual energy production compared with conventional generators. As an option, The Switch offers a highly integrated medium-speed PMG version as an optimized solution.

Features	Advantages
Bearings	Part of integrated structure; designed to last more than 20 years, well beyond turbine lifetime
Neodymium magnets	Strongest commercially available magnets, in a corrosion-resistant metal seal
Windings	Strong form-wound construction offers greater precision and excellent insulation
Cooling concept	Protects the generator effectively against demagnetization and ensures a longer lifetime

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www.theswitch.com

Technical specifications

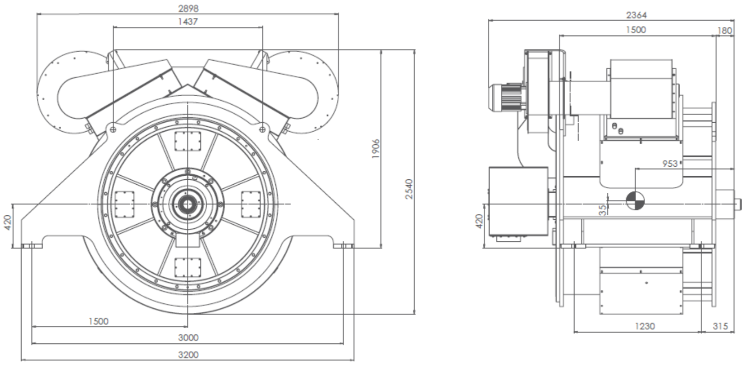
These specifications are based on one nominal operational point example. Our generators can easily be adapted to other operational points.
All generators are also available for medium voltage.
Please contact us to get precise values for your turbine rated parameters.

	PMG1650-150	PMG3120-414	PMG3300-136	PMG3300-365	PMG6400-400[1]
Power [MW]	1.65	3.12	3.3	3.3	6.4
Speed [rpm]	150	414	136	365	400
Shaft-height [mm]	1350	1000	1350	1000	1100
Weight [t]	15	12.7	28	13.9	20
Voltage [V]	690	690	690	690	690
Current [A]	1480	2750	3000	2900	5650
Power factor	0.93	0.95	0.92	0.95	0.95
Efficiency [100% load]	96.4	96.8	96.5	97.5	98.0
Efficiency [75% load]	96.3	96.6	96.5	97.6	98.0
Efficiency [50% load]	96.2	96.1	96.3	97.4	97.8
Efficiency [25% load]	95.4	93.8	95.6	96.4	97.4
Protection class	IP54	IP54	IP54	IP54	IP54
Insulation class	F	F	F	F	F
Thermal class	B	F	B	B	B
Cooling	Air-to-liquid	Air-to-liquid	Air-to-liquid	Air-to-liquid	Air-to-liquid

[1] Preliminary specification data

Technical drawings

Careful material selection for each component and accurate dimensioning of the generators guarantees flawless functionality at all operating points.



The Switch PMG3120-414

Version 6.0, 01/2013

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THE SWITCH
A YASKAWA COMPANY

FPC+ 1000 – 7000 kW

Utility-grade electricity production

FPC+ is the new generation, full-power converter from The Switch. This concept builds on the experience of thousands of units delivered that are achieving solid performance. The affordable, state-of-the-art converter is optimized to work with permanent magnet and induction machines.

Designed for the highest level performance in electricity generation, this robust line of converters ensures future-proof electricity quality to meet the strict international requirements for harmonics, flicker and fault ride-through (FRT).

Optimal power flow control guarantees minimum losses and smooth load transitions. By reducing sensitivity to the network, FPC+ produces a seamless interaction with the grid despite the presence of severe disturbances. New micro-grid functionalities are also available to enhance the proven FRT.

Features	Advantages
Excellent grid performance	High-quality electricity production with FRT
High power density	Reduces number of panels needed
Compact size	Adaptable to match different applications
Versatile	Easy to configure: inline or back-to-back
Control system	User-friendly interface. Expandable design
Rugged IP54-class panel	Designed for harsh conditions and easy access

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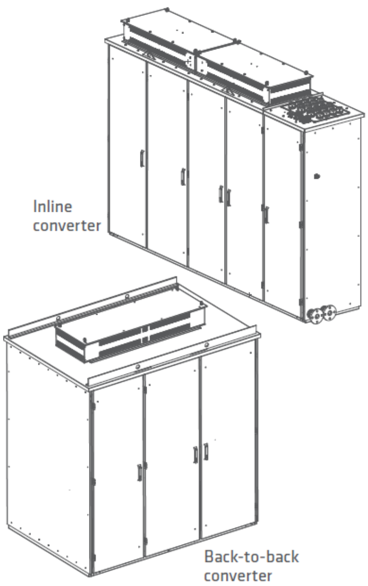
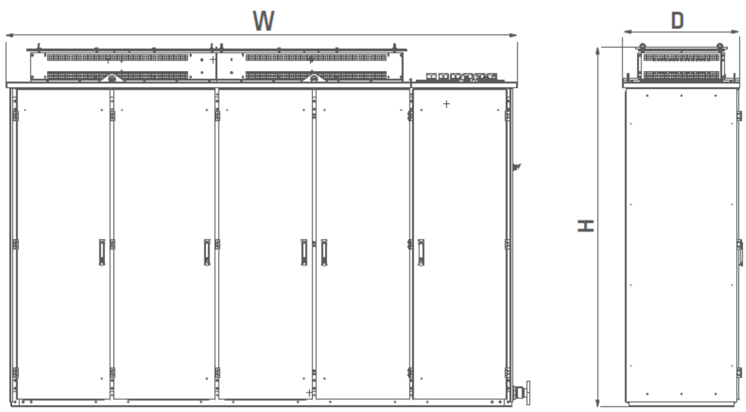
		FPC+ 1000	FPC+ 2000	FPC+ 2500	FPC+ 3000	FPC+ 4000	FPC+ 5000	FPC+ 6000	FPC+ 7000
Frame	Inline	1x22	1x31	1x31	3x22	2x31	2x31	3x31	3x31
	Back-to-back	-	1x19	1x19	1x24	2x19	2x19	2x24	3x19
Power class [MW]		1	2	2,5	3	4	5	6	7
Line current [A]		1050	2100	2600	3100	4150	5100	6200	6200
Generator current [A]		1100	2150	2650	3200	4200	5200	6300	6300
Weight [kg]	Inline	1700	2000	2000	3x1700	2x2000	2x2000	3x2000	3x2000
	Back-to-back	-	2500	2500	4000	2x2500	2x2500	2x4000	3x2500
Dimen-sions for one panel [mm]	Inline	W 2200 H 2009 D 726	W 3100 H 2009 D 726	W 3100 H 2009 D 726	W 2200 H 2009 D 726	W 3100 H 2009 D 726	W 3100 H 2009 D 726	W 3100 H 2009 D 726	W 3100 H 2009 D 726
	Back-to-back	- - -	W 1950 H 2061 D 1362	W 1950 H 2061 D 1362	W 2450 H 2086 D 1362	W 1950 H 2061 D 1362	W 1950 H 2061 D 1362	W 2450 H 2086 D 1362	W 1950 H 2086 D 1362
Nominal voltage		690 V							
Line frequency		50/60 Hz+/- 5 Hz							
Power factor range		0.9 cap – 0.86 ind, with rated active power and grid voltage							
Reactive power production		Field weakening control, voltage control, power factor							
Efficiency		97% at rated point							
Coolant temperature		Max. 45 °C with rated currents, 45–55°C with de-rated capacity							
Ingress protection class		IP54							
Grid harmonics		THD <5% or optionally <1.5%							
Dynamic electric brake		Standard DBU system							
FRT performance		Complies with all international standards							
Fieldbus connectivity		All industrial standards supported (Profbus DP, CANOpen, Modbus RTU, Modbus TCP/IP, EtherCat, Profinet, Interbus)							
Remote management		Yes							



Technical drawing

The modular design allows full redundancy. Failure of one converter does not cause any downtime. The system continues operation at a lower power production rate.



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