Combined Spar and Partially Porous Wall Fish Cage for Offshore Site

COMBINED SPAR AND PARTIALLY POROUS WALL FISH CAGE FOR OFFSHORE SITE

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Abstract – Presented herein is a design concept for an offshore fish farm that combines a spar platform and a partially porous wall fish cage, named COSPAR fish cage. The design features a cylindrical cage with an open net for its bottom portion and a partially porous wall (with specially designed internal section to attenuate strong surface waves) for its top portion. A hybrid concrete and steel, deep draft spar platform carries a wind turbine and a control unit for power supply for remotely controlled fish farming operations. The central spar is connected to the top and bottom of the cylindrical fish cage by frame structures. The top frames are also used as walkways to access the central spar and the bottom frames as ballast compartments for adjusting the draft. By combining fish cage and spar, the meta centre height can be adjusted to induce a low frequency motion response. Moreover, an inherently unbalanced mooring tension problem of a mega-scale cage alone can be resolved by a 4 mooring line system attached to the central spar just below the bottom of the cage. This novel concept of a combined spar and fish cage design is able to overcome challenges of a high energy environment, lack of power supply, and stable mooring system for an offshore fish farm.

Keywords – offshore fish farming, fish cage, spar platform, wind turbine, partially porous wall, wave attenuation

1. INTRODUCTION

Nearshore fish farming industry has to bear criticisms about the degradation of the sheltered sea environment due to fish wastes and uneaten feedstock. Also, nearshore fish farms pose a present risk from competing users for the common nearshore sea space and a restriction on the expansion of fish production. In response to the aforementioned criticisms and a demand for expanding fish production, fish farm operators have begun to consider moving their farms to offshore sites that provide lots more water space and pristine water that has less parasites and pathogens due to better water flow for dispersion of waste (Huguenin, 1997; Tidwell, 2012; Kankainen and Mikalsen 2014; Holm et al., 2017). However, offshore fish farming has to contend with a high energy environment that poses challenges for the structural integrity of the fish cage, and the guarantee of the well-being of the fish. Hitherto, there is a dearth of rigorous studies to develop feasible cost-effective solutions for offshore fish farming as most studies have focussed on nearshore fish farming.

In the open ocean, wave heights can easily reach up to several meters and non-directional irregular wild waves dominate. The wild wave actions induce risk not only a normal operation for fish farming, but fish's well-being as they cause stress and abrasion of fish as well as

problems in feeding. Moreover, fishes have to use lots of energy to swim against the bigger and irregular waves and this leads to a retardation of fish's growth. Therefore, offshore sites are not conducive for fish farming without an appropriate wave attenuation method to lessen the wave forces in the fish cage.

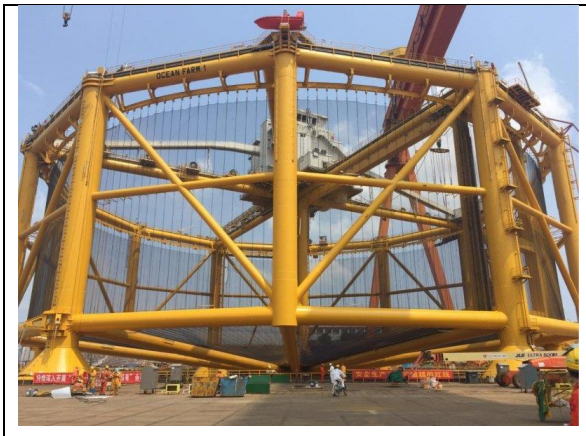
Moreover, offshore sites pose less accessibility for fish farmers to carry out the routine operations of feeding, venturation and maintenance. Thus, offshore fish farming has to lean on remote technologies such as unmanned surveillance and autonomous electric equipment/devices. These supporting devices require a constant power supply (Papandroulakis et al., 2017; Wang et al., 2019). So, it is imperative that offshore fish farms have their own power supply that may be harvested from solar, winds and waves at the site.

The CAPEX (Capital Expenditure) and OPEX (Operational Expenditure) of offshore fish farms will certainly become much higher than nearshore fish farms (Jansen et al., 2016). In order to make offshore farming economically viable, the volume of offshore fish farm has to be much larger than that of nearshore fish farms so as to reach the economy of scale for fish production. So, an offshore fish cage must be mega large with a suitable mooring system and has its own power supply system.

In recent years, a few global fish farming companies have suggested some designs of offshore fish cages and have built them for trial tests at selected offshore sites. Many of these on-going projects make use of semi-submersible platforms and steel cages for offshore fish farming. As semi-submersible platforms have been widely used for the oil and gas industry, it is natural to consider modifying them for offshore fish farming. The semi-submersible platform offers a range of drafts by having ballast tanks in the bottom pontoons and column compartments.

SalMar Group, a Norwegian fish farm operator, has developed the Ocean Farm 1 (see Fig. 1a) in a full-scale pilot offshore fish cage. It is now deployed at 5km off the coast of central Norway. The steel cage has a diameter of 110m, a height of 68m and a volume of 250,000m^3 that is able to accommodate 1.5 million salmons. It is equipped with more than 20,000 sensors, over 100 monitors and control units. Ocean Farm 1 can be submerged in deep water by filling the ballast tanks. It is moored by 8 lines tied at fairleads (that are located at the lower part of the surrounding columns) to the sea bottom foundation. The design is intended for offshore installation in water depths of 100m to 300m and the cage structure is able to withstand 8 m to 10 m significant waves over its 20 years of operating life.

Shenlan 1 (see Fig. 1b) was built by Wuchan Shipbuilding industry Group Co. and it is deployed at 240km off the shore of Rizhao in East China's Shandong province. This offshore fish cage has a diameter of 60m, height of 35m and a volume of 50,000 m^3 that is able to hold 300,000 salmons. The cage has a large ballast volume at the bottom pontoons and columns that allows the cage to be submerged up to 50m below the sea level. Shenlan 1 is a kind of sister fish cage that shares many similarities to Ocean Farm 1 with regard to shape, semi-submergibility and mooring method. However, Shenlan 1 features a centre buoy that is used to generate power for the fish cage by vertical oscillating motions.



(a) Ocean Farm 1
(photo courtesy of Charles Lim)

(b) Shenlan 1
http://www.ccccisc.com/en/haiyanggongchengxiangguan/70.html

Figure 1: Examples of Offshore Fish Cages

The aforementioned Ocean Farm 1 and Shenlan 1 adopt the semi-submergible solution that can temporarily protect the fish and the cage from extreme weather conditions by sinking the cage under water for a period of time. However, these cage designs do not fully protect the fish for the entire farming period when the sites have daily high energetic waves as they are open net cages. It is desirable to have a calm sea state under normal operating condition to ensure fish growth. This requirement poses a strict constraint on the selection of a suitable offshore site. In Australia, Tassal's salmon farmers cannot perform normal duties when the sites are dominated by wave condition exceeding 3m significant wave height (H_s) in a 30-year return period. In addition, cost-effective and constant power supply for fish farm operations are questionable. Despite Shenlan 1 has a power supply from wave energy convertors to harvest wave energy from vertical oscillating motions, it appears contradictory to be harvesting wave energy while at the same time desiring a quiet and conducive environment for fish's well-being and growth.

The authors opine that the following five features be incorporated in the development of a feasible and cost-effective offshore fish cage design:

1. Ensure stable dynamic motions such as heave and pitch to maintain structural integrity of floating system and a safe working condition for workers.
2. Dissipate surface wave energy to produce calm and conducive water environment for fish's well-being and for solving feeding process.
3. Provide a stand-alone power supply to facilitate unmanned surveillance and autonomous systems.
4. Have a simple and stable interactive mooring solution that minimizes and balances the tension forces both windward and leeward mooring lines.
5. Have an integrated system that encompass all the above features.

In view of the above features, the authors propose a novel design concept for offshore fish cage which will be referred to as COSPAR fish cage; an acronym for a COmbined Spar and PARtially porous wall fish cage. The design will allow fish farming companies to expand the choice of potential offshore sites. In this paper, 4 design features of the COSPAR fish cage are

presented with some evidential results of diffraction and coupled mooring analysis based on the potential flow theory and followed by concluding remarks and suggested future work.

2. Design features of COSPAR fish cage

Figure 2 shows the COSPAR fish cage design. It comprises 3 parts: (1) a cylindrical open net fish cage with a partially porous wall (wave fence) at the top portion to block strong surface waves as well as to protect the fish from floating debris and predators, (2) a centrally placed hybrid concrete-steel spar platform that provides the buoyancy for holding a fish cage as well as to carry a wind turbine and control unit and (3) a mounted control unit and wind turbine on the top of the spar to provide the power supply.

The cylindrical cage has an 80m diameter, 39m height and 36m draft. The steel cage has 8 columns, 2 horizontal ring members and 16 radial beams at the base. All steel members have a hollow circular section. The upper part of the cage adjacent to the still water line (SWL) is a 6m high (3m above and 3m below SWL) porous wall with special internal members installed to dissipate waves of 3m high. By arranging a range of porous plates such as high, medium and low for wave transmission, wave run-up and wave reflection, respectively, the incident wave may be reduced by half; thereby creating a reasonable calm internal sea environment that is suitable for fish farming.

The central spar platform has an 82m height, 7.8m diameter and 76m draft. The lower part of the spar up to 38m from the keel line is made from concrete for cost effectiveness as well as to lower the centre of gravity. The upper part is made of steel which is both light and strong.

The cylindrical cage is connected by 4 truss girders (above water) and 16 girders at the base to the spar so that both cage and spar work as a monolithic rigid body. The 4 top girders form walkways to access for the control unit and the wind turbine.

Four fairleads are attached to the spar between 38 m and 40m from the keel line that will tie 4 catenary chains for station keeping. The fairleads are located outside the cage to prevent interference between lines and cage structure as well as to gather the mooring lines to produce a small benthic footprint. The total water volume of the fish cage is about 180,000m^3 that can accommodate about 720,000 salmons by assuming a stock density of 20kg/m^3 and 5kg for matured fish ready for harvesting. Table 1 summarizes the dimensions of the structure and usage of ballast compartments of the COSPAR fish cage.

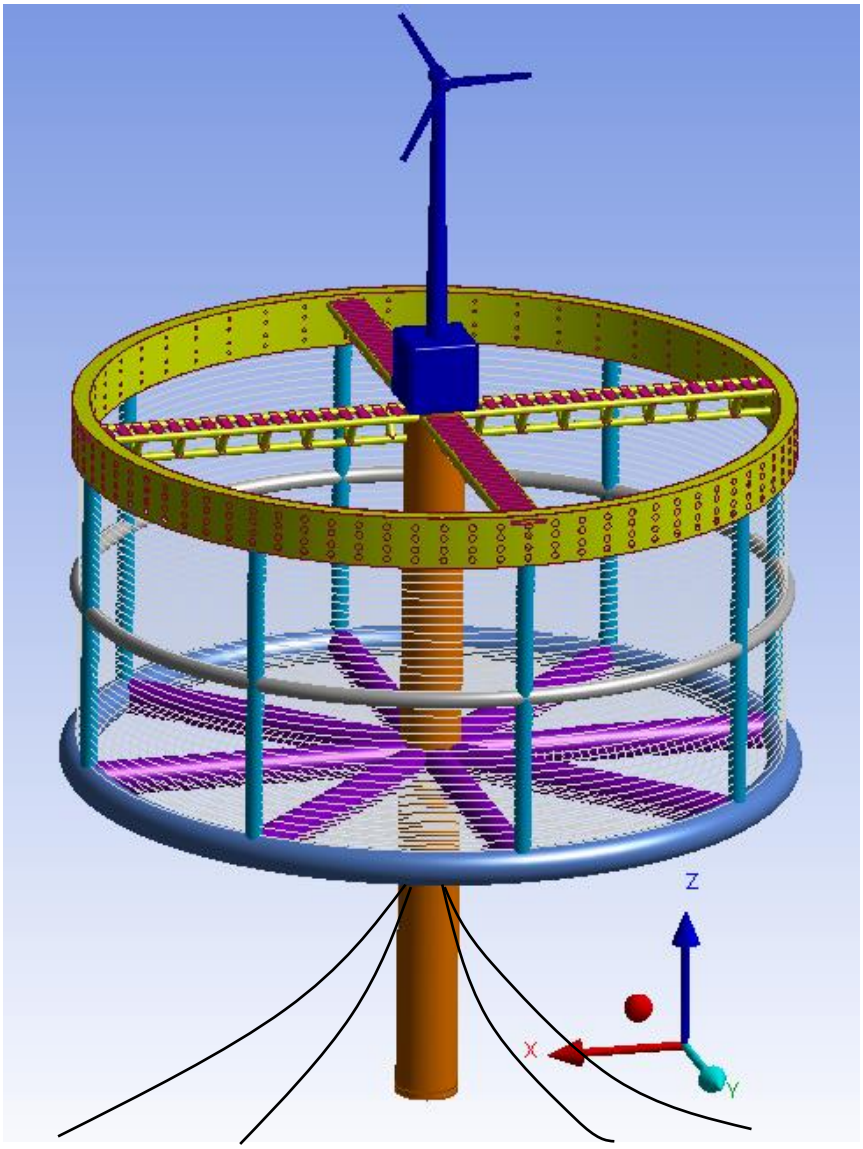


Figure 2: COSPAR cage design

Table 1 Dimensions and ballasting filling of COSPAR

Part Modular	Structural Members	No. of members	Material	Section Diameter or Breadth x Height (m)	Length or circumference (m)	Plate thickness(m)	Fill ballast
Spar	Lower Spar (Outside Cage)	1	Concrete	7.8	38	1.1	No
	Intermediate Spar (Outside cage)	1	Steel	7.8	2	0.06	No
	Upper Spar (Inside cage)	1	Steel	7.8	42	0.06	No

Cage	Wave fence	1	Steel	2 x 6	502	0.045	No
	Vertical frame	8	Steel	2	39	0.03	*Yes/No
	Middle horizontal ring frame	1	Steel	2	502	0.03	*Yes/No
	Bottom frame	8	Steel	4	40	0.03	Yes
	Bottom horizontal ring frame	1	Steel	4	502	0.03	Yes

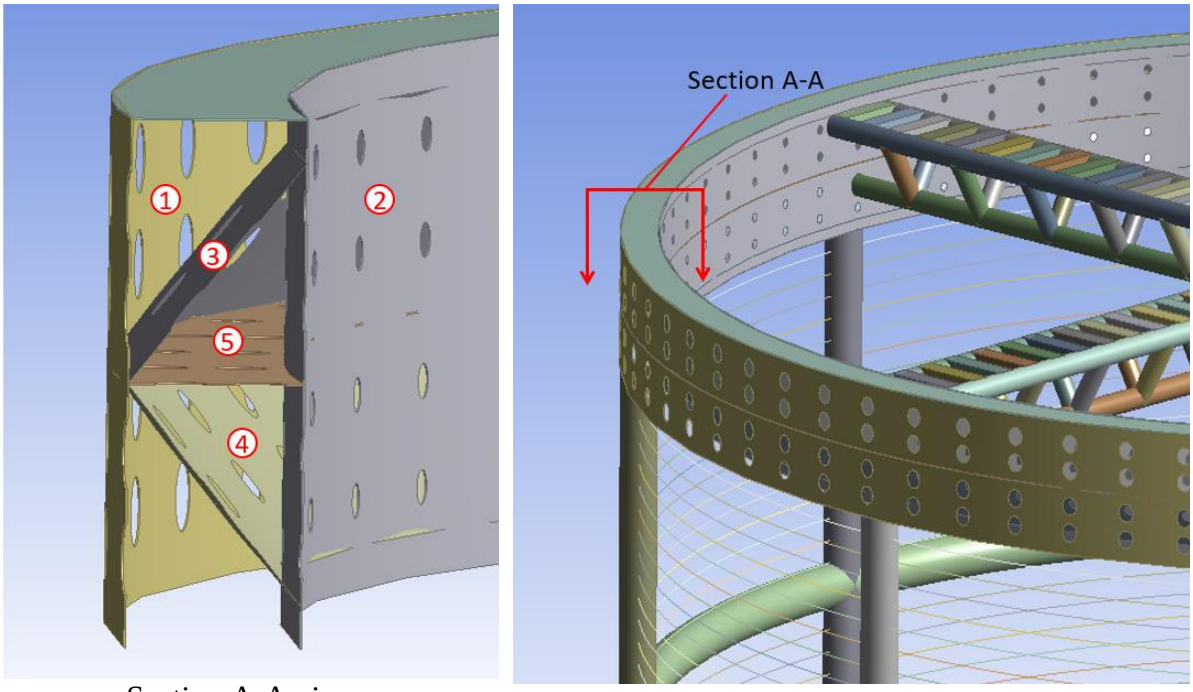
*Yes/No : Vertical frames are filled only for submerged mode

Below, we highlight the design features of COSPAR cage design,

- Design feature 1: Partially porous wall (wave fence) to dissipate wave energy

Attenuating strong waves is an imperative requirement to overcome site restrictions for offshore fish farming. In order to lower wave energy transmission inside the cages, it is necessary to design the cage structures as wave dissipative members that is able to reduce energy from not only incident wave but also from diffraction and reflection waves. As a possible solution, thin porous structure members are introduced as in a breakwater system to protect coastal assets (Sahoo et al., 2000; Besio and Losada, 2008). A breakwater made of material having fine pores has been shown to reduce the hydrodynamic pressure exerted on it. A double porous barrier system is able to reduce both wave transmission and reflection (Qiao et al., 2017). However, owing to the complex wave-wave and wave-structure interactions, the breakwater system tends to significantly affect the hydrodynamic performance of the floating structure (Xiao et al., 2016). There have been several considerations in the design of such a floating breakwater system with respect to buoyancy and floating stability, wave transmission, mooring forces and design of structure for breakwater units (Hegde et al., 2008, Qiao et al., 017). However, it would be costly to build a breakwater system to surround the fish cage in a deep offshore site. Therefore, it is proposed that the breakwater system forms the upper portion of the COSPAR cage design and it will be referred as the wave fence. Figure 3 shows a clearer design of the wave fence that comprises a high porous outer barrier and a low porous inner barrier. Such a design will contribute to controlling the wave transmission and wave reflection, respectively. In addition, internal medium porous plates sloping upwards for incident wave and downwards for reflection wave dissipate energy via wave run-up. Table 2 shows the detail hole sizes to create the different porosities.

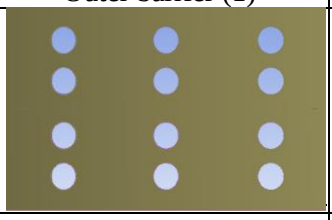
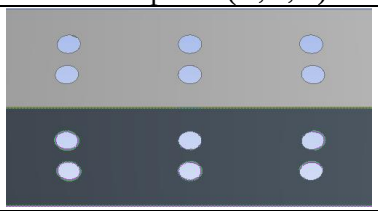
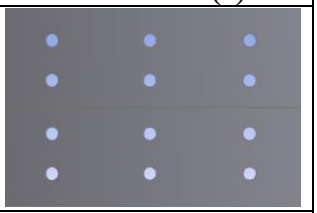
The cage system holds fish by suspending the flexible net at the inner porous barrier and gratings are applied to the outer barrier so as to protect fish from floating debris and invasion of predators. The cage system still keeps the advantage of an open net system for replenishment of water and removal of wastes. Moreover, the solution allows a monolithic rigid body motion that maximizes the efficiency of the wave fence through stable motion response. In addition, by sharing the mooring system for both the cage and the wave fence, capital expenditure may be reduced.



Section A-A view ISO view

Figure 3 : Design of wave fence

Table 2 : Porosity of wave fence plates

Members	Outer barrier (1)	Internal plates (3, 4, 5)	Inner barrier (2)
Picture			
Porosity	High	Medium	Low
Hole size (mm)	800x800	600x600	400x400

- Design feature 2: Combined spar and cage for stable wave response motion

In the offshore wind energy industry, a Spar platform has been tested through experimental and numerical methods as a floater for wind turbine to generate power in an open and deep ocean space. The spar platform has great stability in wave response motions due to its deep draft, low centre of gravity and small wetted surface area. Consequently, the world's first commercialized floating wind farm, Hywind Scotland, adopted a spar platform and successfully deployed it in 2017. Moreover, Utsunomiya et al. (2013) proposed a hybrid spar comprising a prestressed concrete lower half body and a steel upper half body to save construction costs. However, when the spar is used as a floater for wind turbine, wave response motions of the spar is still critical as it significantly affects the performance of the wind turbine. Especially for the horizontal axis wind turbine, pitching motion leads to the unsteady aerodynamic effects on the rotating blades. This results in a large variation of the aerodynamic performance of a floating offshore wind turbine system (Sebastian and Lackner, 2012a, 2012b, 2012c).

On the other hand, in the offshore fish farming industry, semi-submergible floaters are often chosen due to their capability to produce a large farming space by having stiff and strong frame members and submergibility capability (using ballast tanks) to protect cage from extreme storms. However, when the size of floaters become very large, the windward mooring lines are exposed to a far greater tension forces than those lines on the leeward side and this may result in the breaking of the highly stressed lines (Zhao et al., 2019). Moreover, when a wave fence is incorporated as in COSPAR cage design, the semi-submersible floaters may not suitable to produce enough buoyancy force by the slender columns and motion response to the wave resonance may become more susceptible.

Although both offshore fish farming and wind energy industries have not yet developed an ideal design solution to resolve the rigid body motion problem, the authors see great benefits by combining and co-locating the cylindrical fish cage and the floating spar that carries the wind turbine. This is because the cylindrical fish cage has a great horizontal and vertical mass of moment inertia, but it has a relatively large metacentric height that generates too much angular acceleration. On the other hand, a spar has relatively small metacentric height and low angular acceleration that results in a low frequency motion, but its horizontal and vertical stiffnesses are small compare to cage. By combining the two systems and adopting a partially porous wave fence, the harmonized system can share the buoyancy force, reduce wetted surface by porous members, truncated metacentric height, a shifted natural frequency to the low zone and an increased mass moment of inertia. In order to validate the aforementioned characteristics, a comparison study is performed and hydrostatic characteristics are presented for spar only, cage only and COSPAR in Table 3.

Table 3: Hydrostatic characteristics SPAR only, CAGE only and COSPAR

	SPAR only	CAGE only	COSPAR
Centre of Gravity (CoG)	-44 m	-22 m	-34m
Centre of Buoyance (CoB)	-38 m	-19 m	-30m
Wet surface	45 m^2	544 m^2	47 m^2
Metacentric Height (GM)	6.9m	87.7 m	34.2 m
Vertical mass of inertia	$4.871x10^6$ $kg.m^2$	$6.259x10^9 kg.m^2$	$1.167x10^{10}$ $kg.m^2$
Horizontal mass of inertia	$2.288x10^9$ $kg.m^2$	$4.421x10^9 kg.m^2$	$1.049x10^{10}$ $kg.m^2$

Note: wave fence considered as a buoyant part for CAGE due to lack of buoyant force while it is considered a non-buoyant part in COSPAR since it is able to tap on the supplementary buoyancy provided by the spar.

- Design feature 3: Simple and balanced mooring arrangement

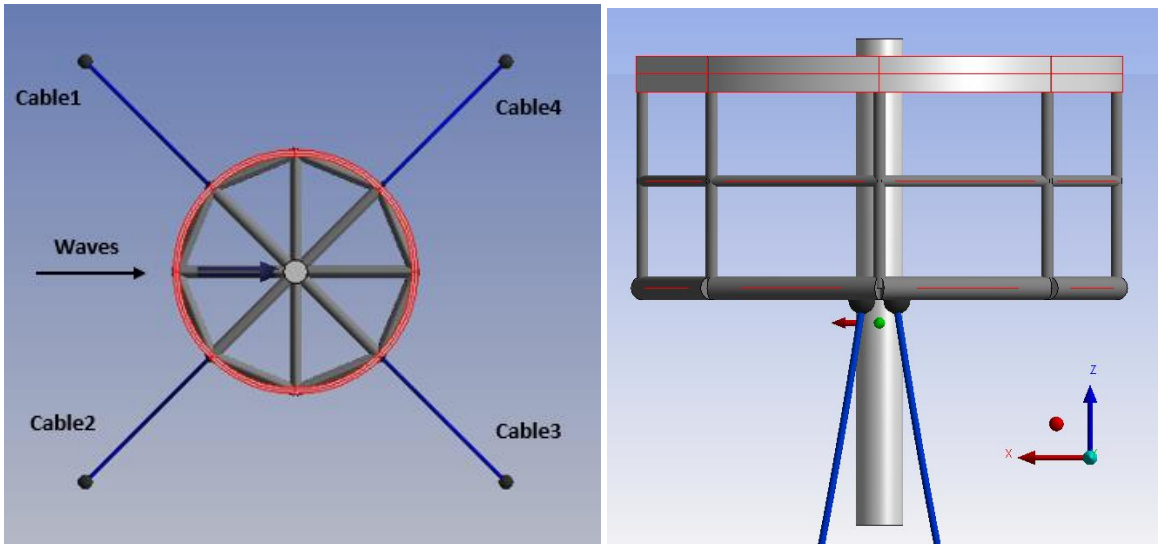
The COSPAR fish cage design is moored by 4 catenary chains tied at fairleads attached in the intermediate part of spar that is outside the cylindrical fish cage (see Figure 4). As offshore fish cage is ultra large from an economic viewpoint, multi mooring lines are often adopted for the mooring of the offshore fish cage. However, the multiple mooring lines produce several drawbacks such as creating a large benthic footprint, complication of installation and unbalanced tension force on windward and leeward sides. Normally, fairleads are located as close as possible to the centre of buoyancy so that dynamic stability is at its best and cable tensions are minimized (Jeon et al., 2013). Therefore, a circular steel cage (such as the Ocean Farm 1) have fairleads installed on the vertical members that results in large distances between the fairleads. On the other hand, COSPAR design is able to shift the centre of buoyancy to a

lower part of the spar; thereby enabling the gathering of mooring lines to a small distance between them. This mooring line arrangement is expected to yield a more stable interactive motion between mooring lines and floating structure as well as to produce a simpler and cheaper solution than say the Ocean Farm 1.

For the mooring analysis, stud link chain cables grade NV K3 with a diameter of 84 mm are chosen with proof load and mass per metre according to the DNVGL RU-SHIP Pt.3 Ch.3 and the effective elastic modulus is determined in accordance with DNVGL-OS-E301 (see Table 4). The fairleads are positioned at 38m below the Still Water Line (SWL) which is 2m below from the bottom of the cage. The distance fairleads from the vertical centreline of the spar (Axis Z) is 3.9m. By assuming a water depth of 200m, anchors are at a radius of 100m from axis Z. The unstretched length of each mooring line is 200m. The transverse drag coefficient of the mooring lines is 2.4 and longitudinal drag coefficient adopted is 1.15

Table 4. Mooring specifications of COSPAR based on DNVGL-OS-E301

Class of mooring lines	Stud link chain NV K3, Diameter 84mm
No. of mooring lines	4
Angle between adjacent lines	90°
Depth of fairleads below SWL	38 m
Distance between fairleads and axis Z	3.9 m
Distance between anchors and axis Z	100 m
Unstretched mooring line length	200 m
Mooring line mass density	152 kg/m
Proof load	3610000 N
Equivalent cross-sectional area	0.011 m^2
Elastic modulus	$5.6x10^{10}$ N/m
Transverse drag coefficient	2.4
Longitudinal drag coefficient	1.15



Top view Front view

Figure 4. Mooring line arrangement

A comparison test has been performed for cage only case and COSPAR case by using ANSYS AQWA for the coupled analysis of diffraction analysis of floating structure interacting with mooring lines. The results show tension force response amplitude operator (RAO) against a unit wave amplitude. Cage only case (Fig. 5) has a wide frequency ranged motion and dominating tension on windward lines whereas COSPAR case (Fig. 6) shows a relatively narrow frequency motion and an evenly distributed motion response.

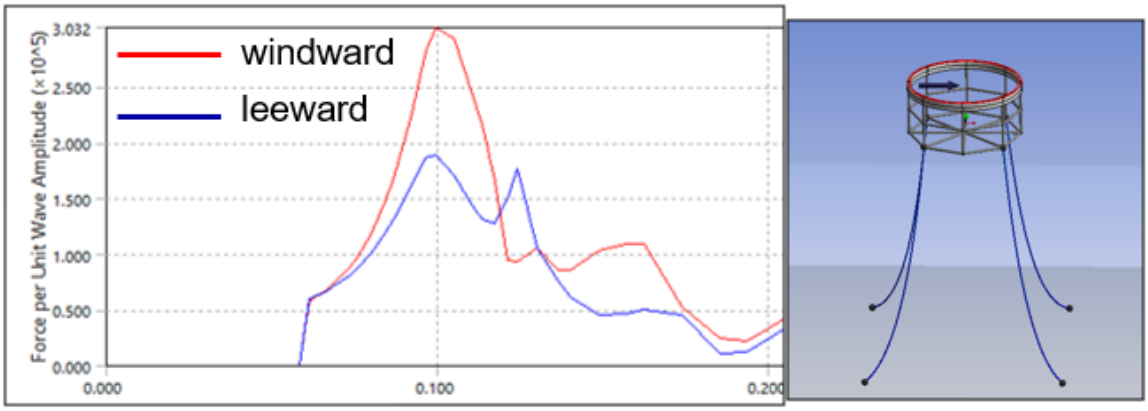


Figure 5. Cage only tension force RAO

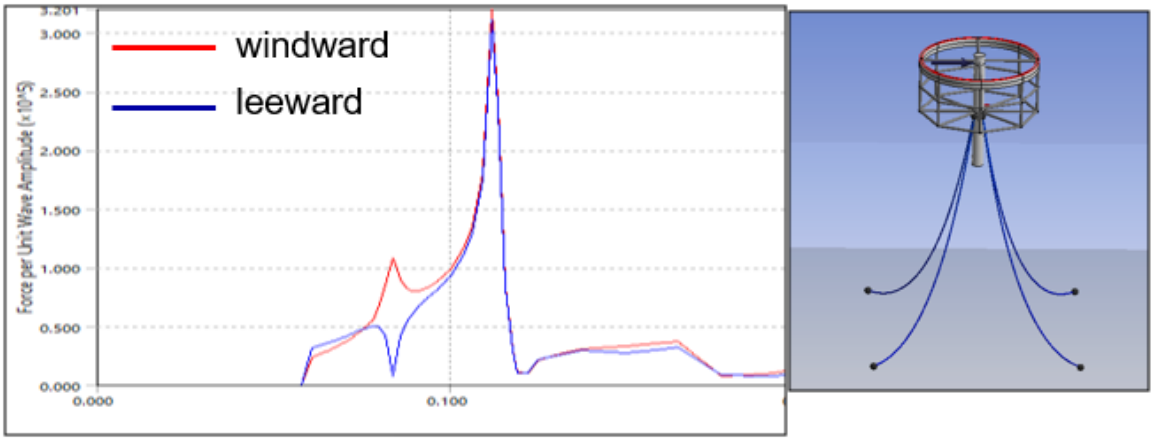


Figure 6. COSPAR tension force RAO

Note: This study does not include the partially porous wave fence as the modelling of a porous surface is not supported in the ANSYS AQWA Therefore, a buoyant wave fence is considered for both cases.

- Design feature 4: Reduction of carbon footprint and efficient power system

The fish farming industry currently rely heavily on fossil fuels for venturation, feeding, lighting, net cleaning, fish bathing and harvesting operations. For example, Tassal (Australia) consume 30 litres of diesel per hour for their 25 fish cages. For a 1.5 year-round operation, this translates to 335 tons of diesel. On the other hand, wind energy industry incurs a significant cost to deliver power over longer distances when the site is far from the coast. By co-locating the floating wind turbine and the fish farm (the end user), it saves costs for the wind energy company and the fish farm operator.

In order to convert wind power for offshore fish farming, it is important to estimate the energy needs associated with farming fish. Direct energy input to fish farming operations encompass a range of activities, including collection and production of juvenile fishes, general

system operation, harvesting, processing, and transport of the product. Troell et al. (2004) introduced approximated figures of energy inputs, as shown in Table 5, for farming salmon. Among energy inputs, at least a fixed capital shall be covered by in offshore condition. Seed and feed energy inputs still need to be supplied by in land and fuelled electricity can be subtracted by wind energy. Therefore, at least 6% of the total energy input accounted for 5,940 EI (kilojoules/kilogram) should be generated by the wind turbine.

Table 5. Energy inputs for farming salmon

Energy inputs(EI) in kilojoules/kilogram for salmon		EI	Percentage %
Fixed capital	Structures/equipment	5,940	6
Operating input	Seed	2,970	3
	Feed	78,210	79
	Electricity, fuel	11,880	12
	Total	99,000	100

With a total target mass of COSPAR of 3600 ton and an expected matured period of 1.5 years, the fish farm requires about 5971 MWh. Considering a general wind turbine efficiency factor of 0.4 to produce the same amount of energy by generating wind turbine, it can be concluded that about 1 MW rated power wind turbine will suffice in supplying power for offshore salmon farming in a COSPAR cage (see Table 6).

Table 6. Required rated power of wind turbine for COSPAR

Volume	180956	m^3
Stock density	20	kg/m^3
Stock weight	3619114	kg
Energy input	5940	kJ/kg
Total energy	21497541537	kJ
Farming period	1.5	yr
Require MWh	5971	MWh
Efficiency factor	0.4	
required rated power	1.1	MW

3. Concluding remarks

Presented herein is COSPAR - a novel fish cage design that has integrated design features of providing stable dynamic motions by coupled spar and cylindrical fish cage, calm water by attenuating wave energy through porous wave fence, a stand-alone power system by having a wind turbine and stable interactive mooring solution with 4 catenary lines attached to the spar and anchored to the seabed.

Although diffraction and radiation analyses were carried out to determine the dynamic motion responses of COSPAR that shows its stability against wave forces, more work is

necessary to refine the design. There are still many uncertainties regarding non-linear viscosity effect such as drag and damping that have to be incorporated in the analysis. Strength evaluation of porous plates is another issue to be considered in final design such as edge reinforcement or protection against corrosion and biofouling. Other alternative material such as a fibre reinforced composite material can be tested when it suits for the design to have more durability in open sea condition.

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