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Dynamic response characteristics of an innovative turretless low motion FPSO hull in central GoM ultra-deep waters

Jun Zou*

Kent Houston Offshore Engineering PLC, 200 Westlake Park Blvd, Suite 1100, Houston, TX 77079, USA

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Abstract. In oil and gas industry, FPSO concept is the most popular hull form and ship shaped hull form dominants the FPSO market. Only a non-ship-shaped hull in operations with minor market shares is the cylindrical FPSO hull with medium to small storage capability. To add contracting options and competitions to reduce field development costs, an innovative turretless low motion hull, eco-FPSO, with 1MM bbls oil storage capacity and suitable for installing topsides modulars and equipping with regular SCRs, was first introduced in Zou (2020a). Dynamic characteristic responses of the eco-FPSO compared to the traditional SS-FPSO hull and DD-Semi platform are presented and discussed in this paper, suitability and feasibility of the proposed hull have been demonstrated and validated through extensive analyses in 10-yrp, 100-yrp and 1,000-yrp hurricanes in ultra-deepwater central GoM.

Keywords: harsh environmental conditions; low motion; minimum airgap; motion RAOs; porch vertical displacement; regular SCRs; ship shaped FPSO; turretless; porch vertical velocity and acceleration RAOs; wave upwelling RAOs

1. Introduction

FPSOs having unique features, such as, eliminating the need for expensive underwater infrastructure; suitable to produce in remote locations and with large storage, are most popular hull forms. The global FPSO market stead growth is anticipated in the forthcoming years. SS-FPSO hulls are dominated the market. Only field proven non-ship-shaped FPSO hull is the cylindrical hull owned by Sevan Marine which occupied the small share of the market with medium to small storage capacity. In harsh environmental conditions, such as North Sea, Western Australia and central GoM, SS-FPSOs are typically fitted with weathervanning system either internal turret or external turret to avoid excessive motions. Sometimes dis-connectable/re-connectable function requirements are needed for turret system. Examples of dis-connectable/re-connectable turret systems are presented in SBM Offshore (2016) and Leverette and Carrico (2017). Thus, complexity, Capital Expenditure (CAPEX), Operating Expenses (OPEX) and risk are further added on.

To improves the economics of deep-water projects, two major FPSO providers: SBM and MODEC, are focusing on reducing delivery cycle time, standardizing the design and the execution plan, de-risking projects and improving quality and safety. Their recent improvements reflected in

*Corresponding author, Ph.D., E-mail: jun.zou@kentplc.com

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product brochures are given in SBM Offshore (2019) and MODEC (2019). Detailed advancements of MODEC new generation FPSOs are systemically presented in Tanaka and Takano (2017); Tanaka *et al.* (2018a, b) and Tanaka and Sogawa (2019) respectively. Even some new features have been claimed, however, from third party cold eyes, there is no fundamental improvement/advancement having been achieved, since the complicated, high CAPEX and OPEX turret system must keep to weathervane and minimize environmental loads on the vessel and mooring/riser system in harsh environmental conditions.

Life-cycle cost analysis (LCCA) study of a FPSO includes CAPEX, OPEX, the lease rate for a FPSO over the life-cycle period and its residual scrap value of hull steel. Based on Nishanth et al (2018), ranks of the most expensive FPSO hull with its mooring system are, the first, FPSO with internal turret; the second, FPSO with external turret and the third, the FPSO with the spread mooring system. Adopting a turret system, not only CAPEX is dramatically increasing but also OPEX is considerably climbing up. To drive down CAPEX and OPEX of field development and improve profitability, there is a strong motivation and market demanding on turretless FPSO in harsh environmental conditions. Eco-FPSO hull development was intended to respond the market calls and its development history and philosophy has been highlighted and presented in Zou (2020a).

The first no-ship-shaped FPSO designed by Sevan Marine started oil production for Petrobras on the Piranema field off Brazil (Reuters 2007). In 2013, DOE funded RPSEA initiated a project by developing turretless FPSO for Remote Ultra-Deepwater Gulf of Mexico Field Development and cylindrical hull was selected per Vidic-Perunovic *et al*. (2014). In 2017, wave basin model tests were carried out and green water has been observed in 100-yrp central GoM hurricane condition and reported in Vidic-Perunovic *et al.* (2017). To meet minimum airgap requirements, same as those production semi-submersible platforms, was extremely challenged for the FPSO with very large volume hull and spread mooring system in harsh environmental conditions. The difficulty on how to mitigate the pronouncedly enhanced wave upwellings, for turretless FPSO in harsh environmental conditions, is well recognized. It is one of our ambitious goals set for the innovative eco-FPSO hull to achieve.

SS-FPSO has some good features, such as suitable for modular topsides, good structural connections between topsides and hull, and safety features with large separate distances. While for a cylindrical FPSO, as found in Hatlestad *et al.* (2019), radial frames in the hull and "bulk weights for electrics and piping are unusually high. Why this should be the case has not been fully clarified, but a possible cause is the fairly unusual topsides layout as a result of the circular hull." In addition, Hatlestad *et al*. (2019) pointed out "The Sevan concept is not designed for efficient construction" and "the circular hull made it difficult to adopt topsides mating or lifting of large modules." Circular deck area makes equipment layout less efficient, and unfavorable for constructions, operations and HSE. For our development, we would like to adopt good features of the SS-FPSO hull offered, get rid of the complicated and expensive turret system, and configure a simple geometry hull having motion characteristics similar or equivalent to a DD-Semi platform suitable for regular SCRs and providing with medium (1MM bbls) to large (2.5MM bbls) oil storage capacity.

The outline of the paper is as follows. First, the brief of the eco-FPSO hull is introduced. Second, descriptions of three hull forms are highlighted. Third, design criteria, definition of heading and coordinate are presented. Fourth, dynamic response characteristics of the proposed eco-FPSO hull, such as motions RAOs, wave upwellings RAOs, SCR porch vertical displacement, velocity, and acceleration RAOs; extreme motions, wave upwellings, minimum airgaps, extreme porch vertical displacements, velocities, and accelerations are revealed and discussed. Finally, main conclusions are drawn, and recommendations are given.

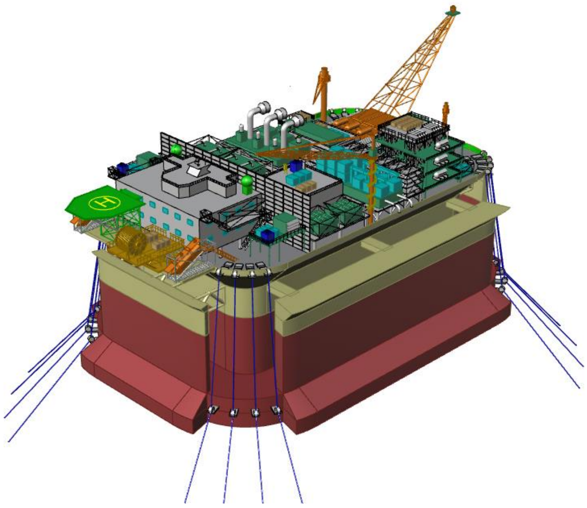


Fig. 1 A Perspective view of an eco-FPSO

2. Brief on the proposed turretless low motion FPSO concept

Discerptions of the proposed turretless low-motion FPSO concept were first introduced and presented in Zou (2020a). Brief on the concept is purly for easy discussions afterwards. A Perspective view of eco-FPSO is displayed in Fig. 1, as an example. Eco-FPSO subsystems are highlighted in sections 2.1 to 2.5 respectively.

2.1 Topsides

As addressed before, modular topsides, similar to the SS-FPSO, are adopted in this design. However, since advancements of topsides layouts of recent FLNG achived, as highlighted in Zou (2020b) and Zou (2021), more efficient larger topside modulars with less required occupyed deck area by multi-floor optimization (Ku *et al.* 2014), without sacifrying HSE, and easy constructions, are employed for this study. Good structural connections between topsides and hull, as discussed in Krekel and Kaminski (2002) and Gourdet (2008), remain unchanged for this concept. Topsides payloads for Base Case in the RPSEA study (Vidic-Perunovic 2014) are 19,740 mt for dry weights and 25,370 mt for operating weight. For this exercise, topsides weights were rounded up to 20,000 mt for dry weights and 25,500 mt for operating weights.

2.2 Eco-FPSO hull

2.2.1 Oil storage capability

Crude oil storage 1MM bbls as well as the requirements of diesel, utility water, potable water and slope were also considered for hull sizing. Details are given in Zou (2020a).

2.2.2 Marine systems

The marine systems are designed for ballast, bilge, fire and safety, control systems and selected topsides utilities.

2.2.3 Ballast

The eco-FPSO is designed with sufficient water ballast to balance vessel trim/heel due to various topsides operations and hull damage scenarios.

2.3 Offloading systems

There are two offloading systems considered for this study, the first option is tandem (stern to bow) offloading and the other way is employing SPM. Feasibility and suitability will be carried out for future study.

2.4 Mooring systems

There are 16 mooring lines in 4x4 pattern and mooring composition is chain-polyester-chain and it is taut mooring system. Diameter of chain is 152 mm and its grade is R4S, and diameter of polyester is 266 mm.

2.5 Riser systems

There are six regular SCRs, four 10-3/4" production risers with 13K wellhead shut-in tubing pressure and two 10-3/4" water injection risers. Reservoir pressure is 20K and Reservoir temperature is 240°F. Details of SCRs configuration data including wall thickness, material properties, hang-off angles, are documented in Zou (2020a).

3. Description of the study cases

3.1 Three hull forms

There are three hull forms, SS-FPSO, eco-FPSO and DD-Semi platform involved in this study and described in Section 3.1.1 to 3.1.3 respectively.

3.1.1 SS-FPSO

Per Moore *et al.* (2017), the Turritella FPSO's nominal production capacity is 60,000 bpd of fluids, 30,000 bpd of produced water and 15 MMscfd of associated gas. The vessel has an oil storage capacity 913,000 bbls which is about 91% of the original Suezmax sized capacity since two forward storage tanks were modified for internal dis-connectable turret system. Its topsides payload is about 8,000 mt and its risers are lazy wave steel risers. An upscaled hull with 1MMbbls has been sized, summarized in Table 1, and illustrated in Fig. 2. It is noted that topsides payloads of the SS-FPSO are about 1/3 of the topsides payloads employed for eco-FPSO sizing in Table 2.

3.1.2 Eco-FPSO

Eco-FPSO hull sizing basis was given in Zou (2020a) and key figures of hull configuration are reproduced and summarized in Table 2 and displayed in Fig. 3 as an example.

3.1.3 DD-Semi platform

To compare motion characteristics of the eco-FPSO, a DD-Semi platform which is suitable for

Table 1 Particulars of the SS-FPSO

Items	Units	Ballast Condition	Fully Loaded Condition
Vessel length (LLP)	m	272.0	
Vessel breadth	m	49.5	
Vessel depth	m	24.0	
Draft	m	9.1	19.5
Topsides payload	mt	8,000	8,000
Oil storage capacity	bbls	50,000	1,000,000
VCG from keel (mass only)	m	12.64	14.53
Roll/pitch/yaw radius of gyration	m	20.59/80.46/80.94	16.20/65.63/66.41

Table 2 Key figures of the proposed eco-FPSO

Items	Units	Ballast Condition	Fully Loaded Condition
Maximum vessel length	m	149.0	
Maximum vessel breadth	m	100.0	
Draft	m	24.5	30.0
Topsides payload	mt	25,500	25,500
Oil storage capacity	bbls	50,000	1,000,000
VCG from keel (mass only)	m	17.0	20.3
Nominal deck dimension (LxW)	m x m	125 x 75	125 x 75
Top of bulwark to MWL	m	26.5	21.0
Bottom of Lower deck to MWL	m	28.5	23.0

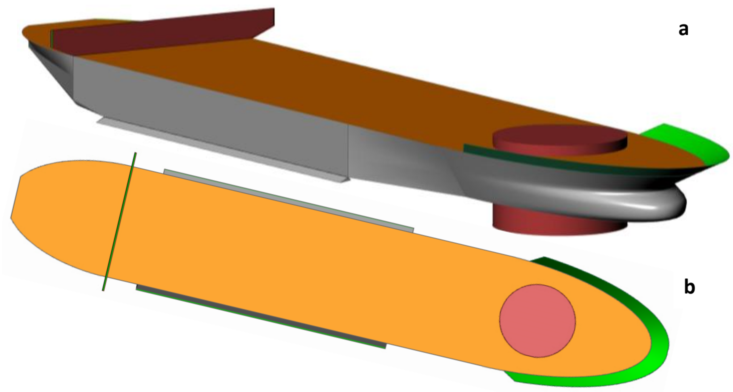


Fig. 2 SS-FPSO hull configuration only: (a) a perspective view of hull and (b) top view

regular SCRs as discussed in Zou (2012), has been sized and its key particulars are summarized in Table 3 and illustrated in Fig. 4.

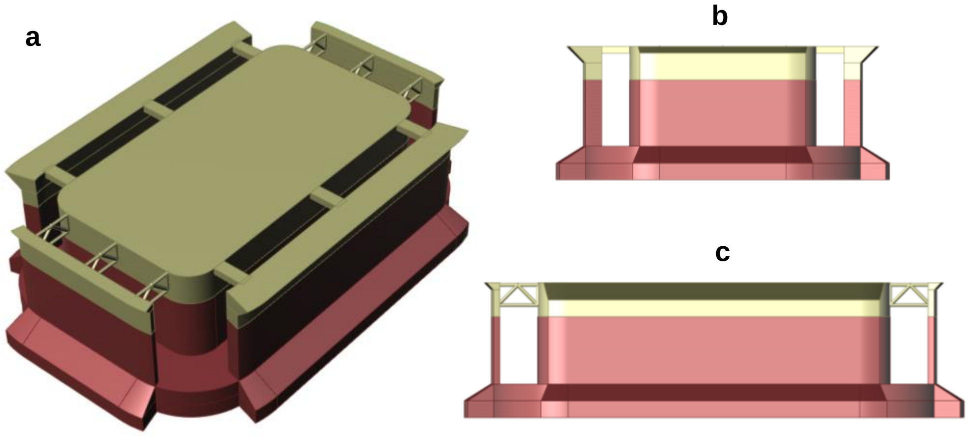


Fig. 3 Eco-FPSO hull configuration only: (a) a perspective view of hull and (b) elevation view – looking FWD-AFT; elevation view – looking port-starboard

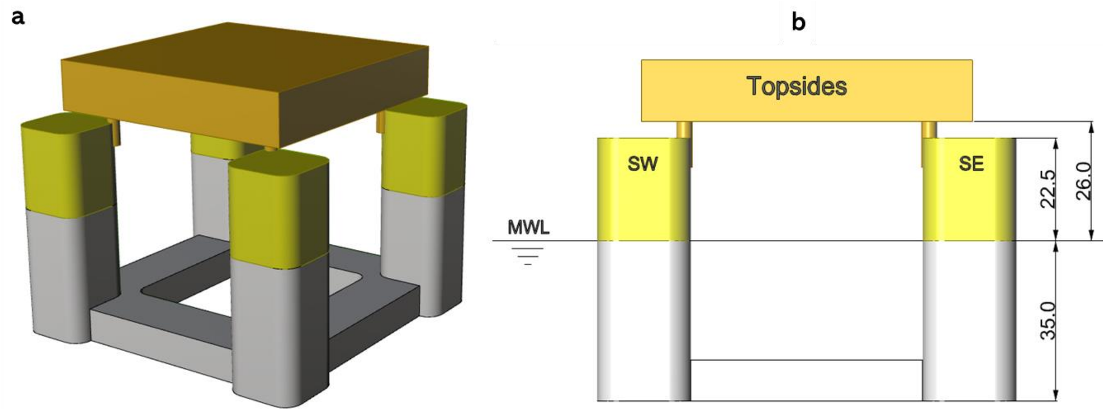


Fig. 4 A DD-Semi platform: (a) a perspective view and (b) elevation view

Table 3 Key particulars of the DD-Semi platform

Items	Units	DD-Semi
Platform draft	m	35.0
Column central to central span	m	73.0
Column side dimension	m	21.0
Pontoon height	m	9.0
Pontoon nominal width	m	17.5
Total column height	m	57.5
Topsides payloads	mt	24,300
Top of column to MWL	m	22.5
Deck post height	m	3.5
Bottom of Lower deck to MWL	m	26.0

Table 4 Summary of heave, roll and pitch natural periods of three hulls

Items	Units	DD-Semi Platform	Ballast Condition		Fully Loaded Condition	
			SS-FPSO	eco-FPSO	SS-FPSO	eco-FPSO
Heave	Sec	22.0	10.0	22.6	12.3	22.8
Roll	Sec	36.4	11.3	34.2	14.0	34.8
Pitch	Sec	36.4	9.7	28.3	11.0	28.6

Table 5 Summary of 10-yrp, 100-yrp and 1,000-yrp hurricane maximum waves

Items	Units	10-yrp Hurricane	100-yrp Hurricane	1,000-yrp Hurricane
Wave spectrum		JONSWAP	JONSWAP	JONSWAP
Significant wave height	m	10.4	15.8	19.6
Peak period	sec	13.1	15.4	17.1
Gamma		2.4	2.4	2.4
Wind spectrum		ESDU	ESDU	ESDU
Hourly wind speed at 10m	m/s	31.2	46.1	57.9
Surface current speed	m/s	1.32	1.94	2.44

3.1.4 Comparisons of natural periods

Comparisons of heave/roll/pitch natural periods of three hulls are summarized in Table 4.

3.1.5 Hull form and its mooring system

Hull form has significant effects on its mooring system in addition to metocean criteria and water depth. For the SS-FPSO, since there is a dis-connectable turret system considered for this study, it only requires 12 moorings for operating sea states and there is no need to consider 100-yrp and 1,000-yrp hurricanes for mooring design. While an eco-FPSO with spread mooring and remains in field for 25 years, its mooring system must design for 100-yrp and 1,000-yrp hurricanes including beam seas. For the DD-Semi platform shown in Fig. 4, there are 12 mooring lines with chain-polyester-chain composition and diameters of chain and polyester are 137 mm and 240 mm respectively. Since an eco-FPSO hull has large volume and blockage to wave and current and large projected area of topsides layout in beam sea for wind, the mooring system for an eco-FPSO not only has more lines but also has larger sizes of chain and polyester as given in Section 2.4.

3.2 Metocean criteria

Extreme metocean data in central GoM are based on API-RP-2MET (2014). 10-yrp hurricanes, 100-yrp hurricanes and 1,000-yrp hurricane maximum wave sea sates are extracted and presented in Table 5. Water depth is 2,500 m for this study.

3.3 Field layout

As described in Sections 2.4 and 2.5, filed layout of mooring lines and SCRs are illustrated in Fig. 5.

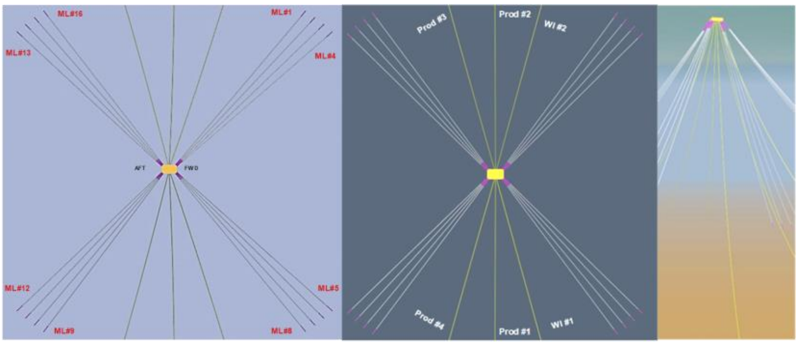


Fig. 5 Field layout – moorings and risers: left, top view of moorings; middle, top view of risers; right, elevation view of moorings and risers

4. Design criteria and definition of heading and coordinate

Since an eco-FPSO is a turretless platform with permeant moorings and staying in field for 25 years, design criteria, such as extreme offsets/heave motions/rotations and extreme lateral accelerations/vertical accelerations, shall be equivalent to those response characteristics of a DD-Semi platform with regular SCRs. No need to repeat here. However, there are some minor differences on requirements on minimum airgaps which are described in Sections 4.1. Definitions of heading and coordinate of the eco-FPSO and the DD-Semi platform are presented in Section 4.2.

4.1 Minimum airgap criteria for a DD-Semi platform and an eco-FPSO

For DD-Semi hull configuration shown in Fig. 4, there are many marine systems related equipment located on top of columns, green water is not allowed on top of column in 100-yrp hurricane while there is no equipment on top of bulwark of eco-FPSO which leads to different criteria on minimum airgaps.

In 100-yrp hurricanes,

- ≥1.5 m with respect to the top of column: a DD-Semi platform
- ≥0.0 m with respect to the top of bulwark: an eco-FPSO

In 1,000-yrp hurricanes,

- ≥ 0.0 m with respect to the bottom of lower deck steel: a DD-Semi platform and an eco-FPSO

4.2 Definition of heading and coordinate

Heading definition for the SS-FPSO is same as the eco-FPSO, thus only the definition of eco-FPSO is selected and shown. Heading definitions of the eco-FPSO and the DD-Semi are illustrated in Fig. 6.

5. Results and discussions

5.1 Motion RAOs

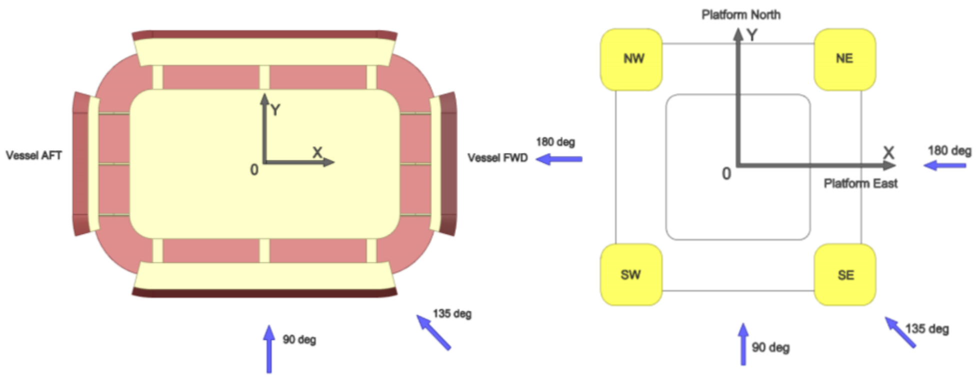


Fig. 6 Heading and coordinate system definitions: left, eco-FPSO; right, DD-Semi platform

There are two design drafts for a SS-FPSO and an eco-FPSO and only one in-place draft for the DD-Semi platform. In all comparison figures, motion RAOs of a DD-Semi platform are identical.

5.1.1 Heave motion RAOs

Comparisons of heave motion RAOs of the SS-FPSO, the eco-FPSO and the DD-Semi in 180 deg, 150 deg, 135 deg, 120 deg and 90 deg are displayed in Fig. 7. From Fig. 7, a few observations are highlighted as follows,

- As shown in Table 4, heave natural periods of ballast condition and fully loaded condition of the SS-FPSO are 10.0 sec and 12.3 sec respectively which are within wave frequency range and strongly relying on sea states. For simplification, only RAOs of the SS-FPSO in 1,000-yrp hurricanes as a representative one shown in Fig. 7. For the ballast condition of the SS-FPSO, since the draft is about 9.1m, the peak of the RAOs was heavily damped and flattened and approaching to 1.0 for wave period longer than 20.0 sec in 90 deg heading.
- Even the turret mooring system was considered for the SS-FPSO, it was assumed the equilibrium positions could result in any wave headings from head sea 180 deg to beam sea 90 deg to investigate the consequences of the failure of the turret system.
- For the SS-FPSO, regardless of ballast condition and fully loaded condition, the RAOs are distinctly different with wave headings varying from head sea to beam sea. Thus, it is essential for the SS-FPSO to install weathervanning turret system in harsh environmental condition to mitigate vessel excessive heave motions. Furthermore, even with turret system, it might require dis-connectable feature for turret system since it still might not meet the specified design criteria in central GoM, example was given in Leverette and Carrico (2017).
- For the eco-FPSO, heave motion RAOs are also different with wave headings varying from head sea to beam sea, however, the variations are much more gradual than those of corresponding RAOs of the SS-FPSO. The RAOs of fully loaded condition are better than corresponding RAOs in ballast condition.
- For the DD-Semi, heave motion RAOs are nearly same for all wave headings since the hull geometry is almost symmetric for various wave headings. It shall point out hull viscous effects can be modeled and accounted through Morrison elements as presented in Das and Zou (2015).

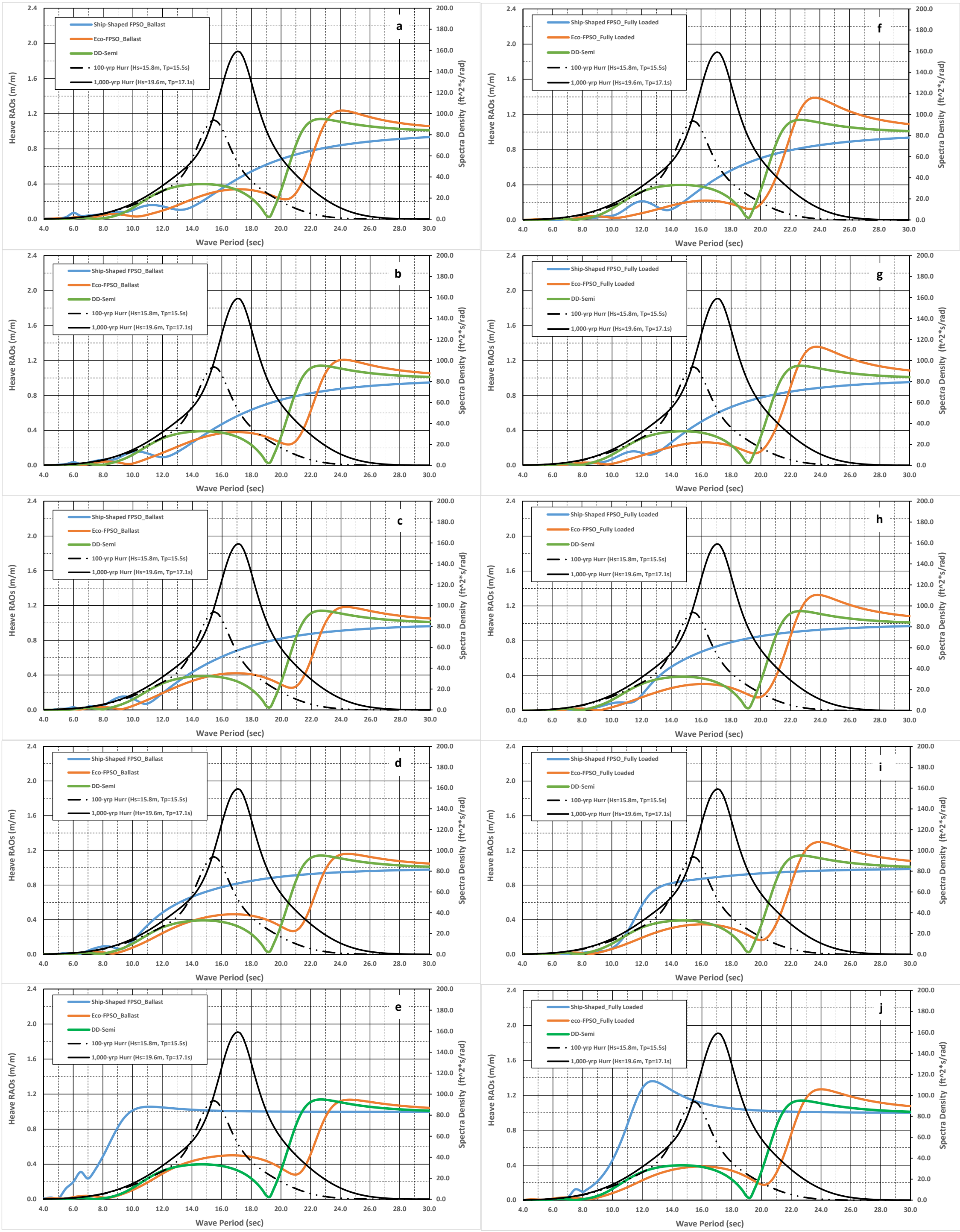


Fig. 7 Comparisons of heave motion RAOs: left, Bal; right, FL; plots “a” and “f”, 180 deg; plots “b” and “g”, 150 deg; plots “c” and “h”, 135 deg; plots “d” and “i”, 120 deg and plots “e” and “j”, 90 deg

- For heave motion RAOs of the eco-FPSO and the DD-Semi platform,
  - o The RAOs of the eco-FPSO (FL) from 180 deg to 135 deg and RAOs of the eco-FPSO (Bal) from 180 deg to 150 deg, are better than those corresponding RAOs of the DD-Semi, while from 120 deg to 90 deg headings, the RAOs of the eco-FPSO (FL) are equivalent to those corresponding RAOs of the DD-Semi.
  - o For 135 deg, the RAOs of the eco-FPSO (Bal) are similar or slightly worse than the corresponding RAOs of the DD-Semi; from 120 deg to 90 deg headings, the RAOs of the eco-FPSO (Bal) are slightly worse than those corresponding RAOs of the DD-Semi.

Comparisons of extreme WF heave motions in 10-yrp, 100-yrp and 1,000-yrp hurricanes varying from 180 deg to 90 deg headings are presented and discussed in Section 5.4.1.

5.1.2 Roll motion RAOs

Since Roll motion RAOs of the SS-FPSO, the eco-FPSO and the DD-Semi in head sea are nearly zero, thus the RAOs in head sea are omitted. Only comparisons of the RAOs of in 150 deg, 135 deg, 120 deg and 90 deg are illustrated in Fig. 8. From Fig. 8, key observations are summarized as follows,

- For the SS-FPSO, regardless of ballast condition and fully loaded condition, roll motion RAOs are significantly varying with wave headings. Similarly, as discussed in Section 5.1.1, it is crucial and necessary for the SS-FPSO to adopt weathervanning turret system in harsh environmental conditions to avoid vessel excessive roll motions.
- The turret mooring system is considered for the SS-FPSO and the hull will rotate around turret system. Its equilibrium position depends on mean loads due to wind, wave, and current and unbalanced loads due to moorings and risers if turret system works normally. However, if the turret system malfunctions and its equilibrium position could result in any wave headings from head sea 180 deg to beam sea 90 deg. It is our goal to investigate the consequences of the failure of the turret system.
- For the eco-FPSO, roll motion RAOs are also varying with wave headings, however, the variations of roll motion RAOs are much more gradual than those of corresponding RAOs of the SS-FPSO. The RAOs of the eco-FPSO (FL) are like corresponding RAOs of the eco-FPSO (Bal) which are considerably improved compared to the corresponding RAOs of the SS-FPSO.
- For the DD-Semi platform, roll motion RAOs are nearly same for all wave headings since the hull geometry is almost symmetric for various wave headings.
- For the eco-FPSO fully loaded condition,
  - o From 150 deg to 120 deg heading, roll motion RAOs of the eco-FPSO are slightly worse to mediumly worse than those corresponding roll motion RAOs of the DD-Semi.
  - o Roll motion RAOs of the eco-FPSO in 90 deg heading are distinctly worse than those corresponding roll motion RAOs in 150 deg to 120 deg headings and significantly worse than those corresponding roll motion RAOs of the DD-Semi.
- For the eco-FPSO ballast condition,
  - o From 150 deg to 120 deg heading, roll motion RAOs of the eco-FPSO are better than those corresponding roll motion RAOs in fully loaded condition, but slightly worse to mediumly worse than those of corresponding roll motion RAOs of the DD-Semi.

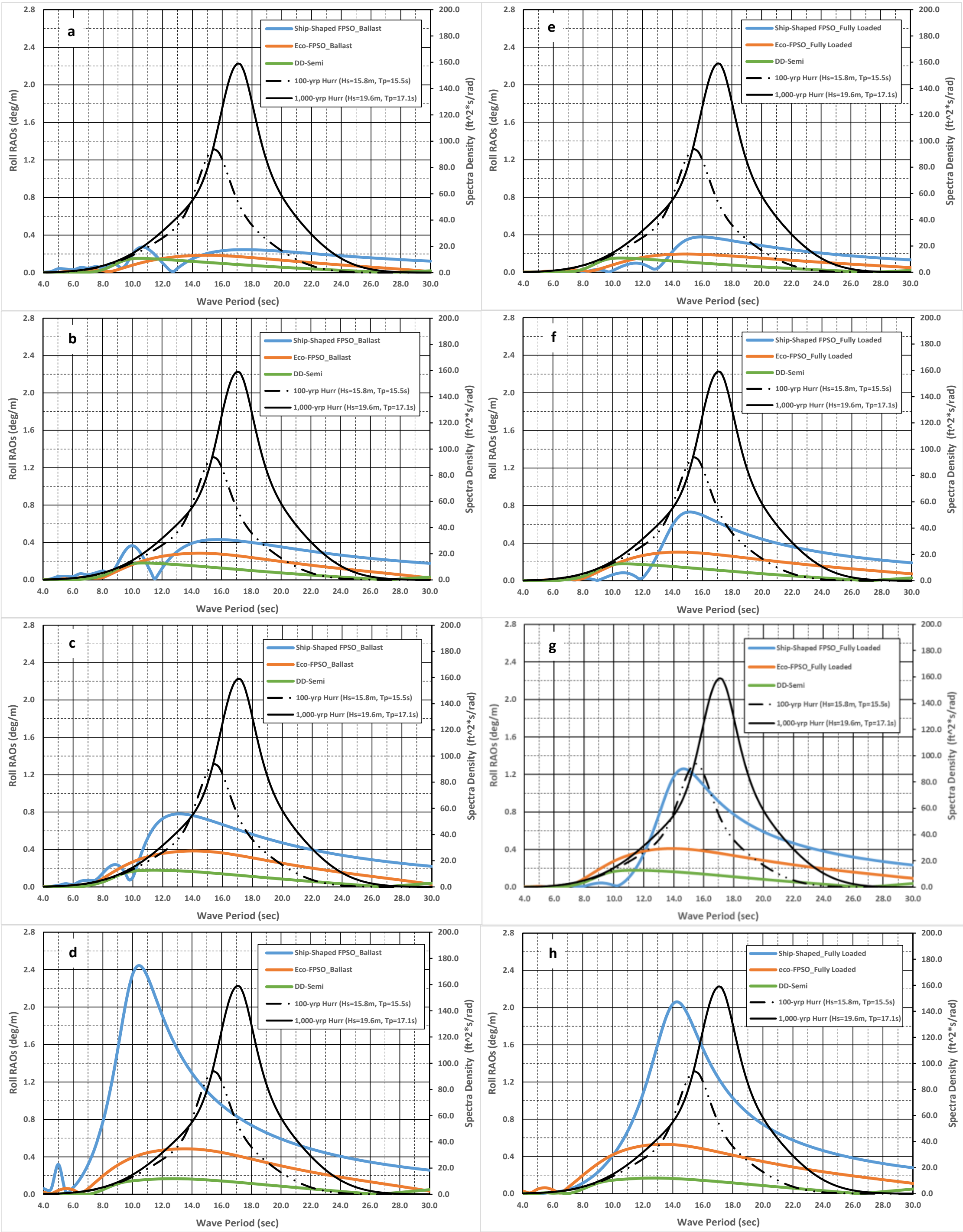


Fig. 8 Comparisons of roll motion RAOs: left, Bal; right, FL; plots "a" and "e", 150 deg; plots "b" and "f", 135 deg; plots "c" and "g", 120 deg and plots "d" and "h", 90 deg

  - Similarly, like fully loaded condition, roll motion RAOs of the eco-FPSO in 90 deg heading are noticeably worse than those corresponding roll motion RAOs in 150 deg to 120 deg headings and considerably worse than those corresponding roll motion RAOs of the DD-Semi.
- For the eco-FPSO regardless of ballast condition and fully loaded condition, roll motion RAOs are either slightly worse to mediumly worse or considerably worse than those corresponding roll motion RAOs of the DD-Semi which indicate the selection of the SCRs porch location is crucial and shall be closer to the center of the vessel to minimize the negative impacts of roll response characteristics of the eco-FPSO.

Comparisons of extreme WF roll motions in 10-yrp, 100-yrp and 1,000-yrp hurricanes varying from 150 deg to 90 deg headings are given and discussions on roll response characteristics of three hulls are denoted in Section 5.4.2.

5.1.3 Pitch motion RAOs

Since pitch motion RAOs of the SS-FPSO, the eco-FPSO and the DD-Semi in beam sea are nearly zero, thus pitch motion RAOs in beam are omitted. Only comparisons of pitch motion RAOs of in 180 deg, 150 deg, 135 deg and 120 deg are denoted in Fig. 9. From Fig. 9, a few findings are given as follows,

- For the SS-FPSO,
  - Regardless of ballast condition and fully loaded condition, pitch motion RAOs are similar for both 180 deg and 150 deg headings.
  - Pitch motion RAOs of fully loaded condition are slightly worse than those corresponding pitch motion RAOs of ballast condition for both 135 deg and 120 deg headings.
  - Unlike heave motion RAOs and roll motion RAOs of the SS-FPSO, pitch motion RAOs are not distinctly varying with wave headings but gradually changing.
- For the eco-FPSO, pitch motion RAOs are also varying with wave headings from head sea to beam sea, the variations of pitch motion RAOs are in gradual fashion. The RAOs of the eco-FPSO (FL) are slightly better than those corresponding RAOs of the eco-FPSO (Bal). Pitch motion RAOs of the eco-FPSO are significantly improved compared to the corresponding RAOs of the SS-FPSO in both ballast condition and fully loaded condition.
- For the DD-Semi, pitch motion RAOs are nearly same for all wave headings since the hull geometry is almost symmetric for various wave headings.
- For the eco-FPSO,
  - Pitch motion RAOs of the eco-FPSO in both ballast condition and fully loaded condition in 180 deg to 120 deg headings are slightly worse to mediumly worse than those corresponding RAOs of the DD-Semi.
  - As described in Section 5.1.2, pitch motion RAOs of the eco-FPSO in both ballast condition and fully loaded condition in 180 deg to 120 deg headings are slightly worse to mediumly worse than those corresponding pitch motion RAOs of the DD-Semi, thus, considering the weakness of roll and pitch motion response characteristics of the eco-FPSO with respect to those of the DD-Semi, the preferred porch locations for SCRs shall be arranged closer to the center of the vessel to minimize the vertical motions induced by roll and pitch motion at SCRs' porch locations. More discussions are presented in Section 5.3.5.3.

Comparisons of extreme WF pitch motions in 10-yrp, 100-yrp and 1,000-yrp hurricanes varying from 180 deg to 120 deg headings are presented and addressed in Section 5.4.3.

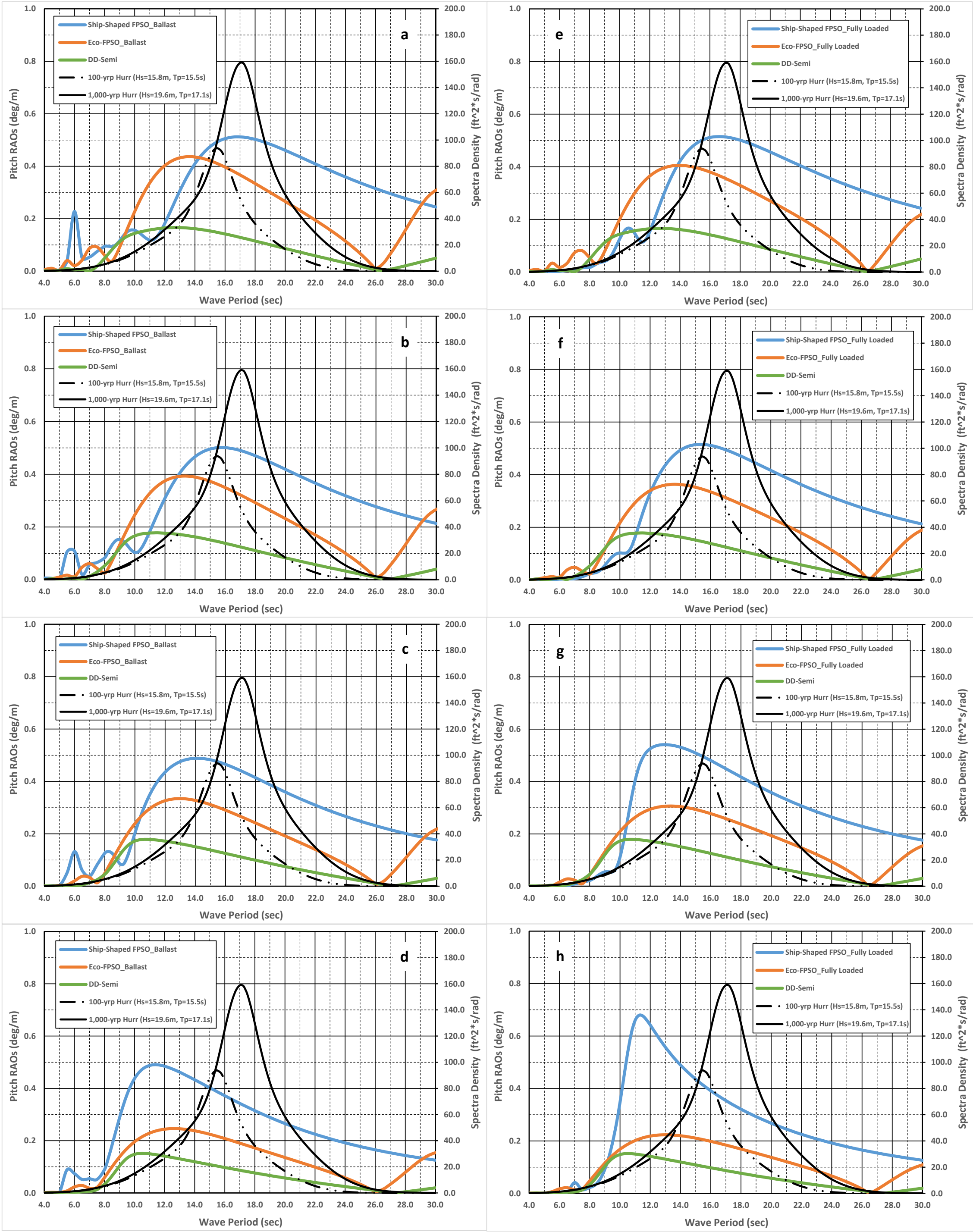


Fig. 9 Comparisons of pitch motion RAOs: left, Bal; right, FL; plots "a" and "e", 180 deg; plots "b" and "f", 150 deg; plots "c" and "g", 135 deg and plots "d" and "h", 120 deg

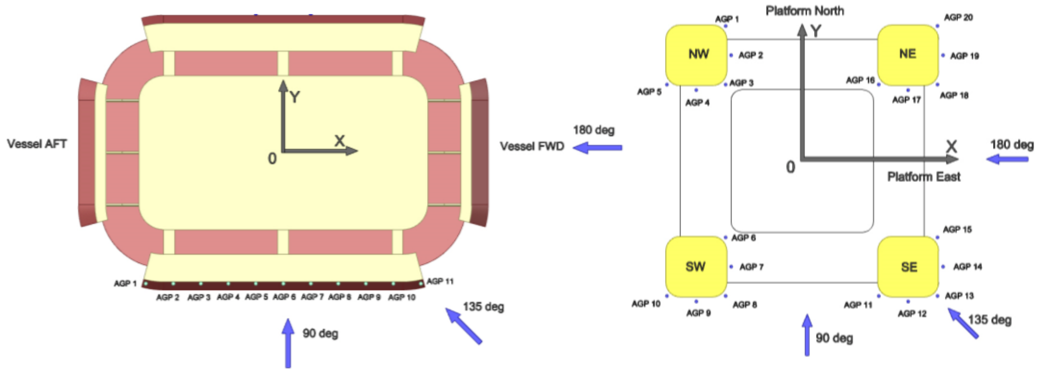


Fig. 10 Points of wave probes for airgaps: left, for the eco-FPSO; right, for the DD-Semi

5.2 Wave *upwelling* RAOs

5.2.1 General

As stated in Section 1, our goal is to develop an innovative hull concept having equivalent motion characteristics like a DD-Semi platform suitable for regular SCRs but turretless with medium to large oil storage capacity in harsh environmental conditions. With permanent mooring system in field for 25-year or longer service life, minimum airgap criteria including beam sea shall be equivalent to those of a DD-Semi platform. In this section, the most critical wave upwelling RAOs have been identified, compared, and presented through screening exercises and results are presented in Section 5.2.3.

5.2.2 Points of wave probes

To monitor minimum airgaps, critical points of wave probes have been distributed and illustrated in Fig. 10. For the eco-FPSO, there are 11 points distributed along vessel longitudinal direction since beam sea is most critical heading. For the DD-Semi platform, there are 20 points around vicinities of 4 columns with respect to wave heading from head sea, 180 deg to beam sea, 90 deg.

5.2.3 Comparison of wave upwelling RAOs

From Fig. 10, after screening results of significant WF wave upwellings of the eco-FPSO, the wave upwelling RAOs at point AGP 6 in 90 deg have been found to be the most critical, thus, it was selected as the representative wave upwelling RAOs for comparison. For the DD-Semi, all headings from 180 deg to 90 deg having been screened, the most critical wave upwelling RAOs are identified at point AGP 3 as shown in the right sketch in Fig. 10. From Table 2, the still water clearances of top of bulwark and bottom of lower deck steel of the eco-FPSO in the fully loaded condition are 4.5m lower than those corresponding still water clearances in ballast condition, therefore, fully loaded condition of the eco-FPSO was believed to be more critical for satisfying minimum airgap criteria in 100-yrp and 1,000-yrp hurricanes and was considered and selected for comparisons of the wave upwelling RAOs verse the DD-Semi. The wave upwelling RAOs of these two chosen locations and headings are compared and displayed in Fig. 11.

From Fig. 11, some key observations are highlighted and discussed as follows,

- From wave period 14.0 sec to 21.5 sec, wave upwelling RAOs of the eco-FPSO are lower than those of corresponding wave upwelling RAOs of the DD-Semi.

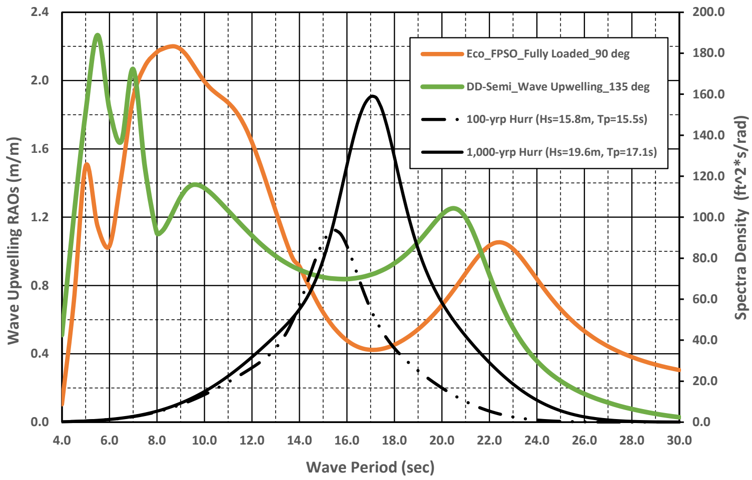


Fig. 11 Comparison of wave upwelling RAOs, eco-FPSO vs DD-Semi

- From wave period 21.5 sec to 30.0 sec, wave upwelling RAOs of the eco-FPSO are higher than those of corresponding wave upwelling RAOs of the DD-Semi.
- From wave period 7.0 sec to 14.0 sec, wave upwelling RAOs of the eco-FPSO are considerably higher than those corresponding wave upwelling RAOs of the DD-Semi.
- Wave spectra of 100-yrp hurricane and 1,000-yrp hurricane are also plotted in Fig. 11.
    - The wave upwelling RAOs of the eco-FPSO have been tuned for 1,000-yrp hurricane which resulted in not optimal wave upwelling RAOs with respect to 100-yrp hurricane wave spectrum since wave peak of 1,000-yrp hurricane is 1.6 sec longer than that of 100-yrp hurricane.
    - Since it is impossible to tune wave upwelling RAOs for both 100-yrp and 1,000-yrp hurricanes simultaneously, there is one approach to achieve best “balanced resultant” optimal minimum airgaps in both 100-yrp and 1,000-yrp hurricanes since it is equally important to meet minimum airgap criteria. The wave upwelling RAOs of the DD-Semi have been tuned for achieving best “balanced resultant” optimal minimum airgaps in both 100-yrp and 1,000-yrp hurricanes.

Comparisons of extreme WF wave upwellings in 100-yrp and 1,000-yrp hurricanes are highlighted and discussed in Section 5.5.2.

5.3 SCRs porch RAOs

5.3.1 General

As addressed in Section 1, the innovative eco-FPSO hull not only gets rid of turret system but also offers motion characteristics suitable for regular SCRs like the DD-Semi. Thus, SCRs porch RAOs of the eco-FPSO for both ballast condition and fully loaded condition shall be equivalent to those corresponding porch RAOs of the DD-Semi platform. Comparisons of SCRs porch RAOs include,

- Porch vertical displacement (PVD) RAOs,
- Porch vertical velocity (PVV) RAOs,

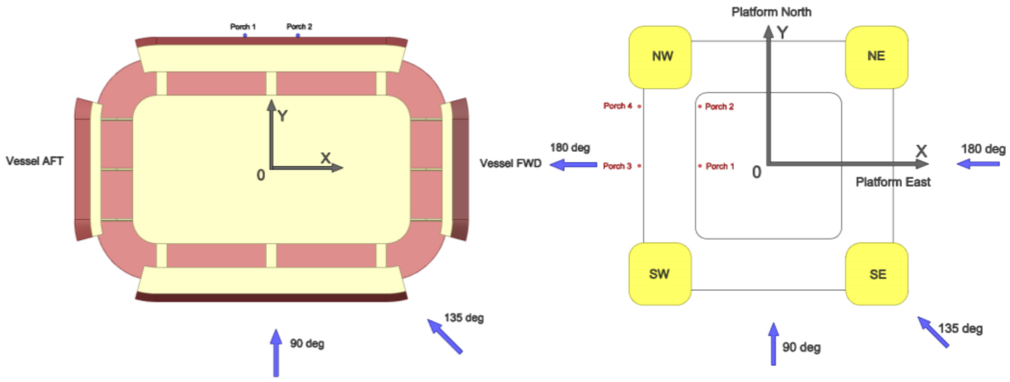


Fig. 12 Locations of SCRs porches: left, porches 1 and 2 for the eco-FPSO; right, porches 1 and 2 located at inside of west pontoon; porches 3 and 4 located at outside of west pontoon for the DD-Semi

- Porch vertical acceleration (PVA) RAOs.

In this section, SCRs porch locations will be introduced in Section 5.3.2 and comparisons of the above mentioned RAOs are presented in Section 5.3.3 to 5.3.5 respectively.

5.3.2 Locations of SCRs porches

Locations of SCRs porches of the eco-FPSO and of the DD-Semi are denoted in Fig. 12. There is an alternative location for the eco-FPSO which is placed at the central moonpool (10 m x 10 m, not shown).

5.3.3 SCRs porch RAOs of the DD-Semi platform

5.3.3.1 PVD RAOs

As shown in the right sketch of Fig. 12, there are four porch locations, two porches (porches 1 and 2) located at inside of west pontoon; two porches (porches 3 and 4) located at outside of west pontoon. porches 1 and 2 are closer to platform center than that of porches 3 and 4 which will result in relatively smaller vertical displacement, velocity, and acceleration than the corresponding design values at porches 3 and 4. However, to pull-in SCRs at porch 1 and porch 2 at good pull-in angles, normally we need have an opening at the middle of topsides to install pull-in winches which make topsides layout more complicated and less efficient. In this study, DD-Semi hull configuration has been sized to meet regular SCRs motion criteria by considering SCRs porches on outside of west pontoon. It is our intention to show there are some advantages of vertical displacement, velocity and acceleration at SCRs porches located inside of west pontoon if design parameters get worse during design processes and re-locating SCRs porches from outside of pontoon to inside of pontoon might be an alternative solution if needed.

DD-Semi SCRs PVD RAOs of porches 1 to 4 from 180 deg to 90 deg are illustrated in Fig. 13. In addition, DD-Semi vertical displacement RAOs at CG are also included as reference to gauge roll and pitch motions induced vertical displacements at the specified SCR porch locations.

5.3.3.2 PVV RAOs

The PVV RAOs of the DD-Semi at porches 1 to 4 from 180 deg to 90 deg are displayed in Fig. 14. In addition, DD-Semi vertical velocity RAOs at CG are also plotted as a reference measure.

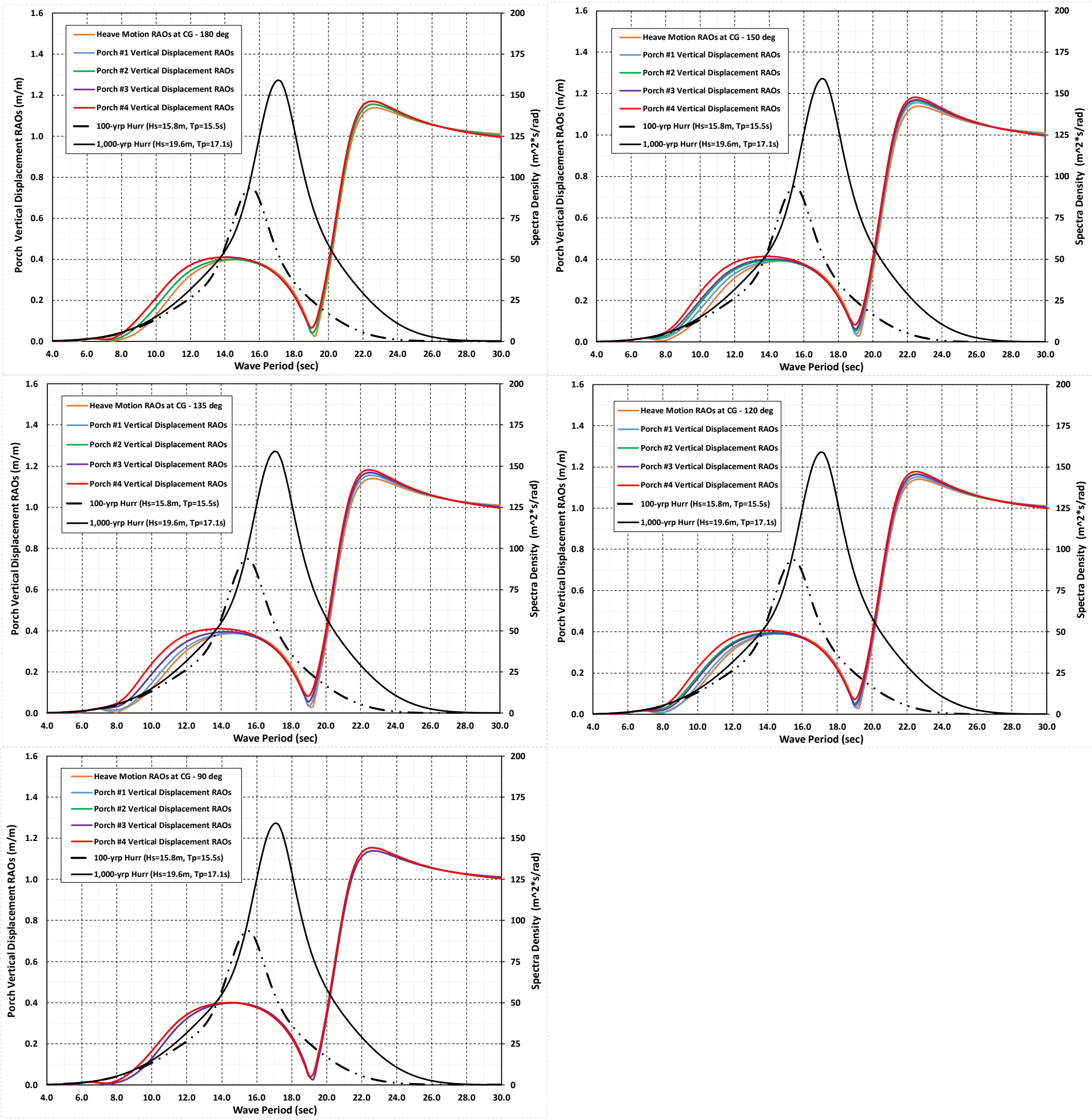


Fig. 13 Comparisons of PVD RAOs of the DD-Semi

5.3.3.3 PVA RAOs

The PVA RAOs of the DD-Semi CG, porches 1 to 4 from 180 deg to 90 deg are plotted in Fig. 15.

From Fig. 13 to Fig. 15, a few observations are summarized as follows,

- In 180 deg, PVD, PVV, and PVA RAOs at porches 1 and 2 are same and PVD, PVV, and PVA RAOs at porches 3 and 4 are identical. PVD, PVV, and PVA RAOs at porches 3 and 4 are slightly worse than those corresponding RAOs at porches 1 and 2 and slightly higher than those corresponding RAOs at platform CG.
- In 150 deg, 135 deg and 120 deg headings, PVD, PVV, and PVA RAOs at porch 4 are always the worst among 5 referenced locations.

- In 90 deg, PVD, PVV, and PVA RAOs at porch 1, porch 3 and at CG are same and PVD, PVV, and PVA RAOs at porch 2 and porch 4 are identical.

In summary, PVD, PVV, and PVA RAOs at porch 4 are always the worst among 5 referenced locations for 150 deg, 135 deg and 120 deg and one out of two worse locations for 180 deg and 90 deg headings.

5.3.4 SCRs porch RAOs of the eco-FPSO

5.3.4.1 PVD RAOs

As displayed in the left sketch in Fig. 12, there are two porch locations, porch 1 (-10 m, 50 m) and porch 2 (10 m, 50 m). In addition, PVD RAOs at vessel CG (moonpool, not shown) are also added as references to provide a measure for evaluating vertical motions induced by vessel roll and pitch motions with arms of porches to vessel center. PVD at porches 1 and 2 from 180 deg to 90 deg headings in both ballast and fully loaded condition are illustrated in Fig. 16.

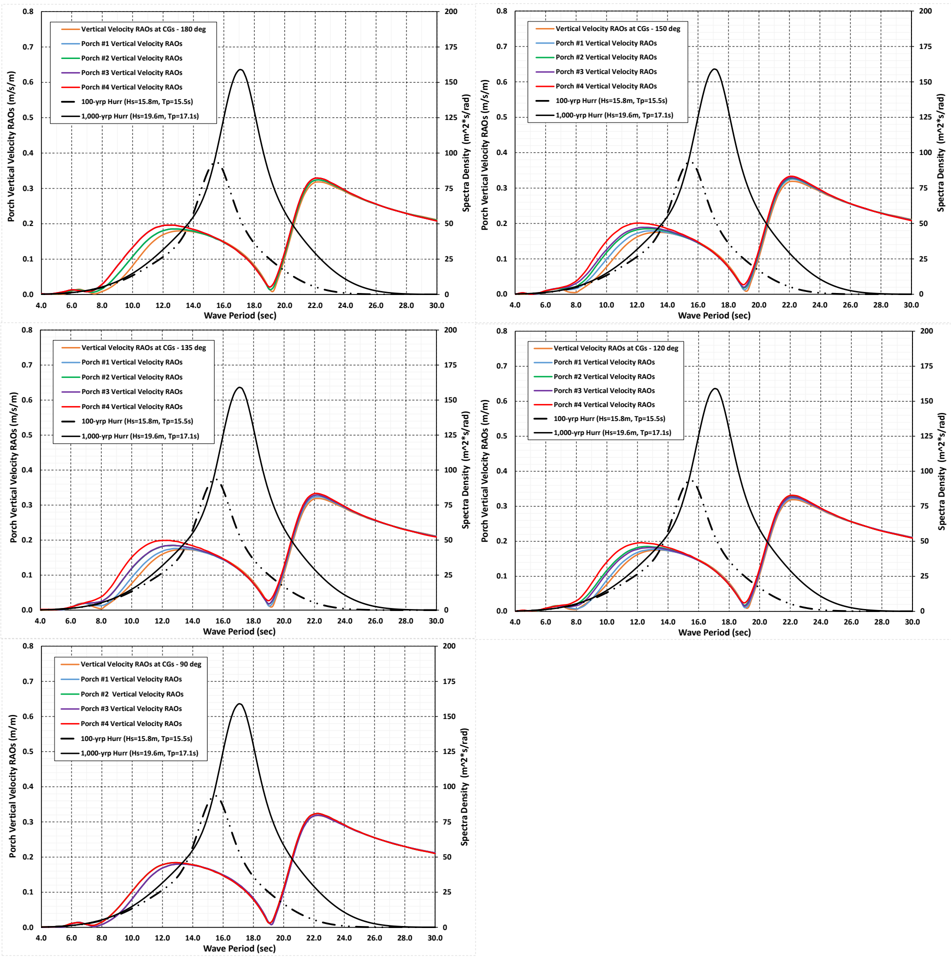


Fig. 14 Comparisons of PVV RAOs of the DD-Semi

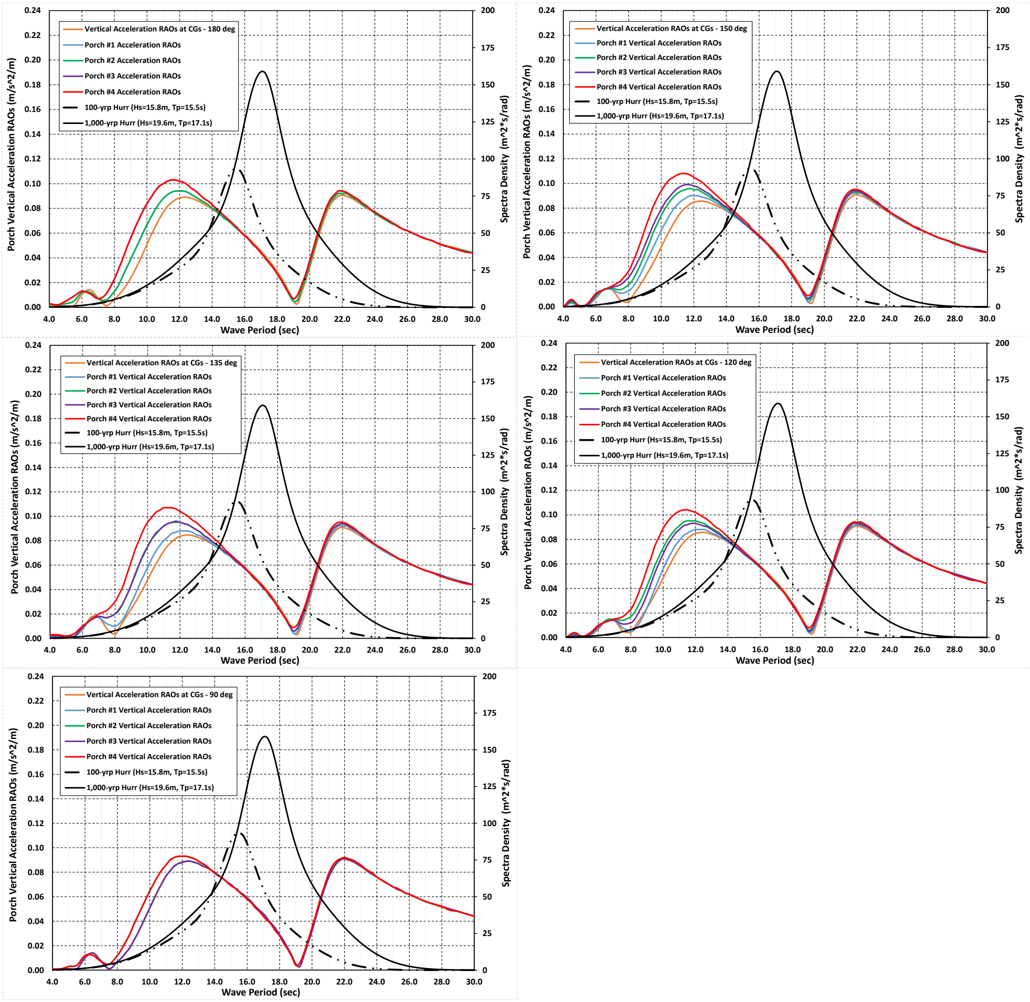


Fig. 15 Comparisons of PVA RAOs of the DD-Semi

5.3.4.2 PVV RAOs

The PVV RAOs of the eco-FPSO at vessel CG (moonpool, not shown), porches 1 and 2 from 180 deg to 90 deg headings in both ballast condition and fully loaded condition are illustrated in Fig. 17.

5.3.4.3 PVA RAOs

The PVA RAOs of the eco-FPSO at the CG, porches 1 and 2 from 180 deg to 90 deg headings in both ballast condition and fully loaded condition are displayed in Fig. 18.

From Fig. 16 to Fig. 18, a few findings are given below,

- From 180 deg to 120 deg headings,
    - For wave periods ≤ 20.0 sec, PVD, PVV, and PVA RAOs of the eco-FPSO (FL) at vessel CG, porches 1 and 2 are lower than those corresponding RAOs of the eco-FPSO (Bal) at vessel CG, porches 1 and 2 respectively.

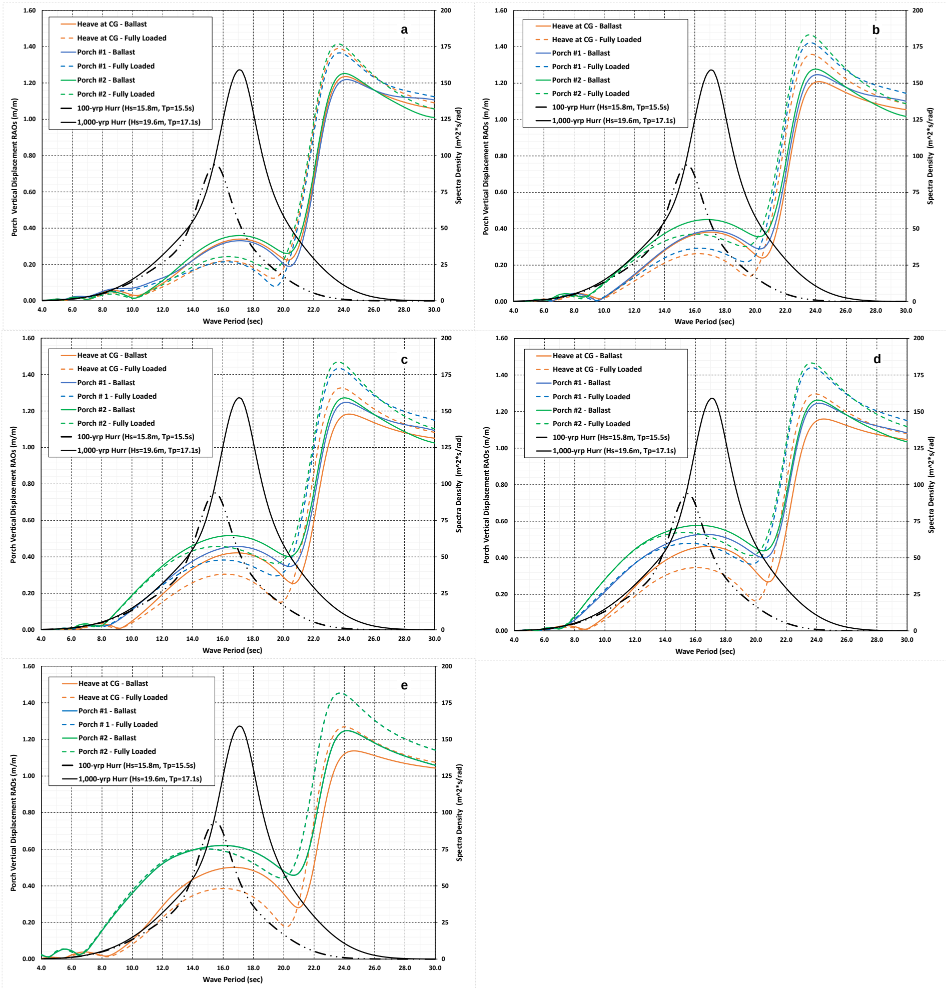


Fig. 16 Comparisons of the PVD RAOs of the eco-FPSO: (a) 180 deg, (b) 150 deg, (c) 135 deg, (d) 120 deg and (e) 90 deg headings

  - For wave periods ≥ 20.0 sec, PVD, PVV, and PVA RAOs of the eco-FPSO (FL) at vessel CG, porches 1 and 2 are higher than those corresponding RAOs of the eco-FPSO (Bal) at vessel CG, porches 1 and 2 respectively.
- For 90 deg heading,
  - For wave periods ≤ 20.0 sec, PVD, PVV, and PVA RAOs of the eco-FPSO (FL) at vessel CG are lower than those corresponding RAOs of the eco-FPSO (Bal) at vessel CG.
  - For wave periods ≤ 20.0 sec, PVD, PVV, and PVA RAOs of the eco-FPSO (FL) at porches 1 and 2 are equivalent or slightly lower than those corresponding RAOs of the eco-FPSO (Bal) at porches 1 and 2.

For wave periods ≥ 20.0 sec, PVD, PVV, and PVA RAOs of the eco-FPSO (FL) at vessel CG, porches 1 and 2 are higher than those corresponding RAOs of the eco-FPSO (Bal) at vessel CG, porches 1 and 2 respectively.

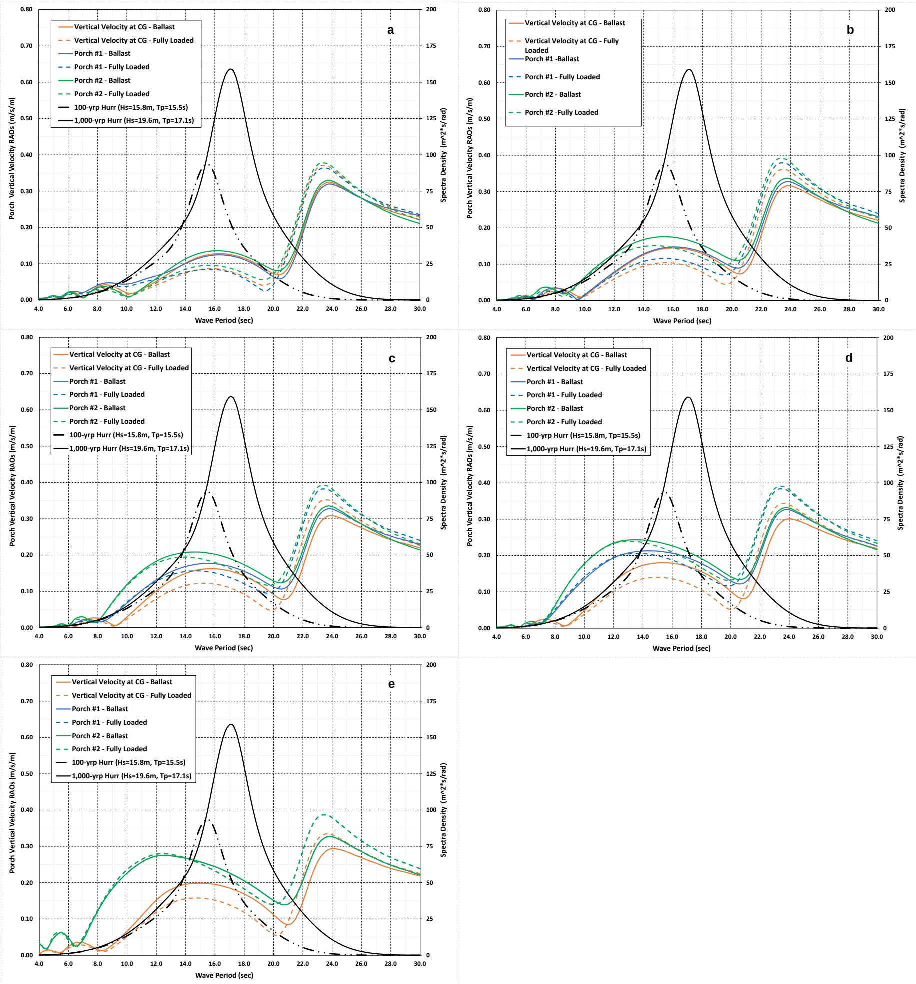


Fig. 17 Comparisons of the PVV RAOs of the eco-FPSO: (a) 180 deg, (b) 150 deg, (c) 135 deg, (d) 120 deg and (e) 90 deg headings

- In short, four PVD, PVV, and PVA RAOs of the eco-FPSO are chosen as representative displacement, velocity, and acceleration RAOs to compare with those corresponding RAOs of the DD-Semi at porch 4. These four representative locations for the eco-FPSO are given below,
  - Vessel CG for ballast condition
  - Vessel CG for fully loaded condition
  - Porches 1 and 2 for fully loaded condition

5.3.5 Comparisons of SCRs porch RAOs: eco-FPSO vs DD-Semi

5.3.5.1 Comparisons of PVD RAOs: eco-FPSO vs DD-Semi

By employing of the PVD RAOs of the DD-Semi at porch 4 as a measure, four representative PVD RAOs of the eco-FPSO are directly compared and illustrated in Fig. 19.

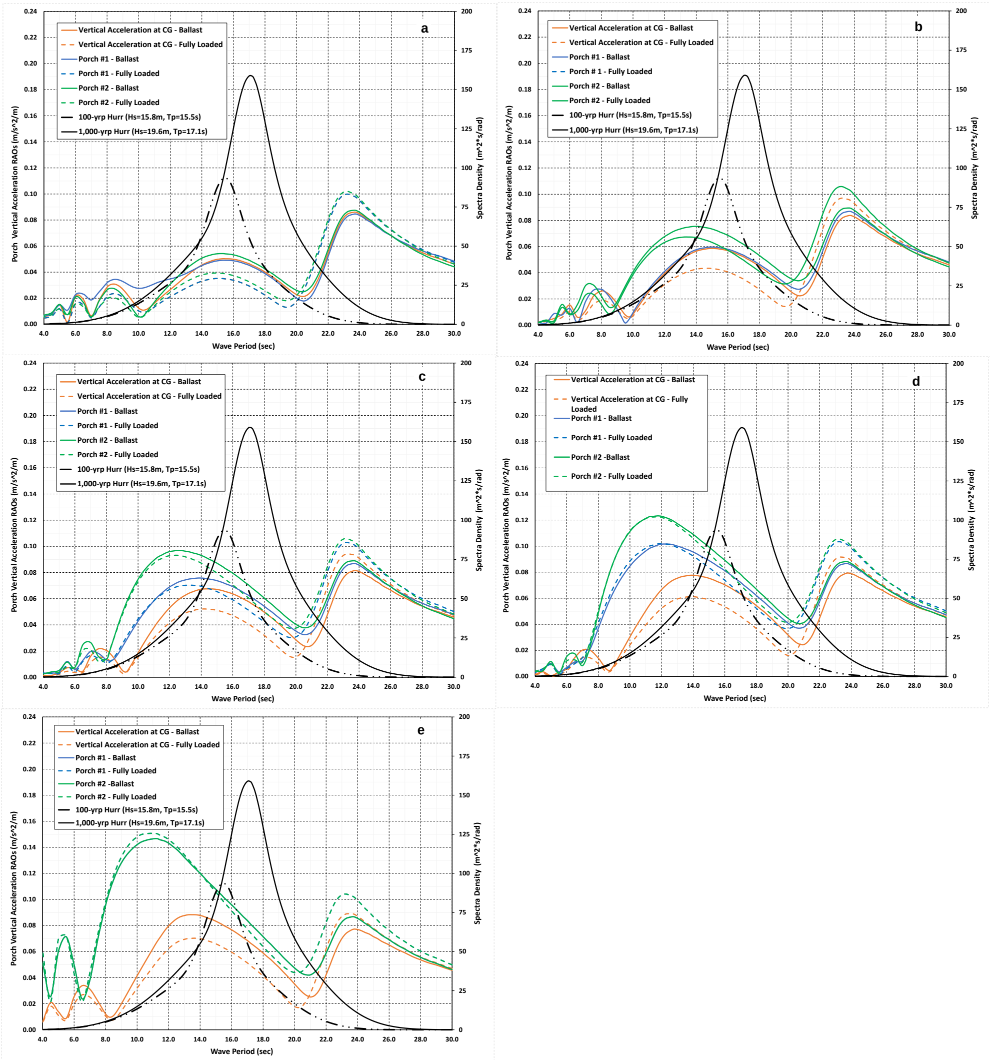


Fig. 18 Comparisons of the PVA RAOs of the eco-FPSO: (a) 180 deg, (b) 150 deg, (c) 135 deg, (d) 120 deg and (e) 90 deg headings

5.3.5.2 Comparisons of PVV RAOs: eco-FPSO vs DD-Semi

By considering of PVV RAOs of the DD-Semi at porch 4 as a measure, four representative PVV RAOs of the eco-FPSO are directly compared and shown in Fig. 20.

5.3.5.3 Comparisons of PVA RAOs: eco-FPSO vs DD-Semi

By adopting PVA RAOs of the DD-Semi at porch 4 as a measure, four representative PVA RAOs of the eco-FPSO are directly compared and displayed in Fig. 21.

From Fig. 19 to Fig. 21, some key observations are presented as follows,

- From Fig. 19(a) to Fig. 19(e), the PVD RAOs; Fig. 20(a) to Fig. 20(e), the PVV RAOs; Fig. 21(a) to Fig. 21(e), the PVA RAOs of the eco-FPSO at vessel center for fully loaded condition are lower than those corresponding RAOs of the DD-Semi at porch 4.

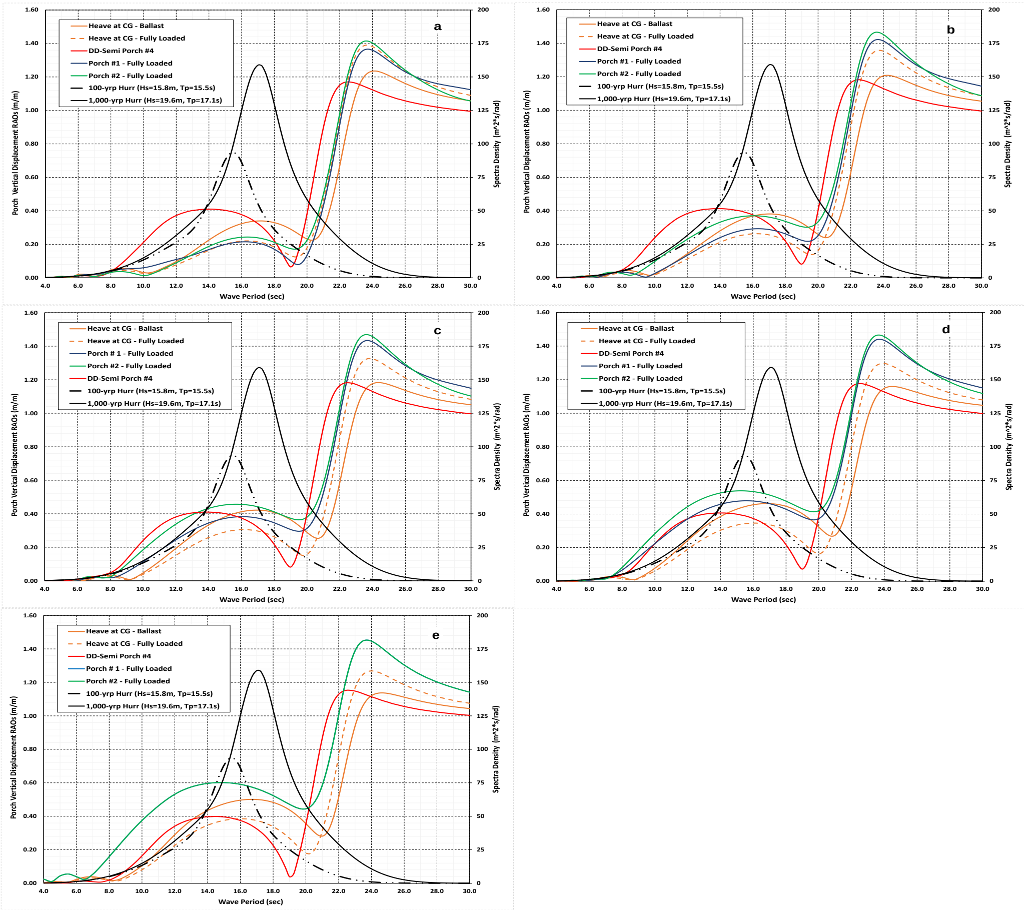


Fig. 19 The PVD RAOs: (a) 180 deg, (b) 150 deg, (c) 135 deg, (d) 120 deg and (e) 90 deg headings

- From Figs. 19(a) and 19(b), four representative PVD RAOs; Figs. 20(a) and 20(b), four representative PVV RAOs; Figs. 21(a) and 21(b), four representative PVA RAOs of the eco-FPSO are all lower than those corresponding RAOs of the DD-Semi at porch 4.
- From Figs. 19(c), 20(c) and 21(c),
    - The PVD, PVV and PVA RAOs of the eco-FPSO at vessel center for ballast condition and at porch 1 for fully loaded condition are equivalent to those corresponding RAOs of the DD-Semi at porch 4.
    - The PVD, PVV and PVA RAOs of the eco-FPSO at porch 2 for fully loaded condition are higher than those corresponding RAOs of the DD-Semi at porch 4.
- From Figs. 19(d) and 19(e); Figs. 20(d) and 20(e); Figs. 21(d) and 21(e),
    - The PVD, PVV and PVA RAOs of the eco-FPSO at vessel center for ballast condition are slightly higher in 120 deg and higher in 90 deg than those corresponding RAOs of the DD-Semi at porch 4. For this study, omni-directional environmental condition was assumed. In real projects, there will most likely be directional extreme sea states, thus they can be mitigated by aligning vessel beam sea with benign extreme sea states

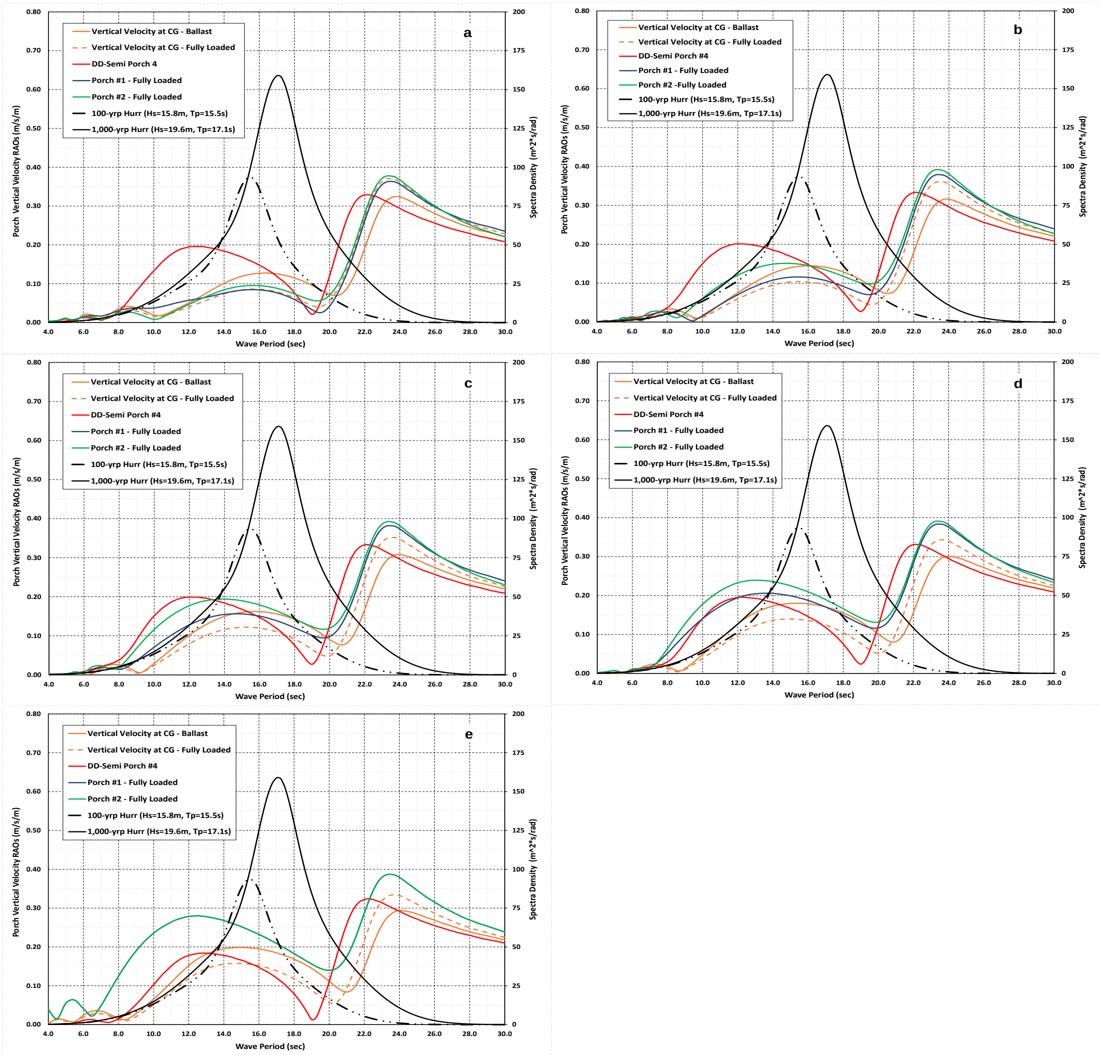


Fig. 20 The PVV RAOs: (a) 180 deg, (b) 150 deg, (c) 135 deg, (d) 120 deg and (e) 90 deg headings

The PVD, PVV and PVA RAOs of the eco-FPSO at porches 1 and 2 for fully loaded condition are higher in 120 deg and considerably higher in 90 deg than those corresponding RAOs of the DD-Semi at porch 4. Unless there are very strong directional extreme sea states in the field, these two locations are not suitable for regular SCRs.

5.4 Extreme WF motions

Extreme WF motions including extreme motions of heave, roll and pitch are summarized in Section 5.4.1 to 5.4.3 respectively.

5.4.1 Extreme WF heave motions

5.4.1.1 Extreme WF heave motions of the SS-FPSO

Table 6 Extreme WF heave motions of the SS-FPSO

	Significant Wave-Frequency (WF) Heave Motions (m)					
	Ballast Condition			Fully Loaded Condition		
Headings	10-yrp	100-yrp	1,000-yrp	10-yrp	100-yrp	1,000-yrp
180 deg	1.74	4.73	7.90	1.85	4.86	8.14
150 deg	2.24	5.94	9.38	2.31	6.22	9.80
135 deg	3.26	7.62	11.27	3.56	8.29	12.06
120 deg	5.10	10.04	13.84	6.05	11.45	15.33
90 deg	8.81	14.19	18.01	10.58	16.66	20.62

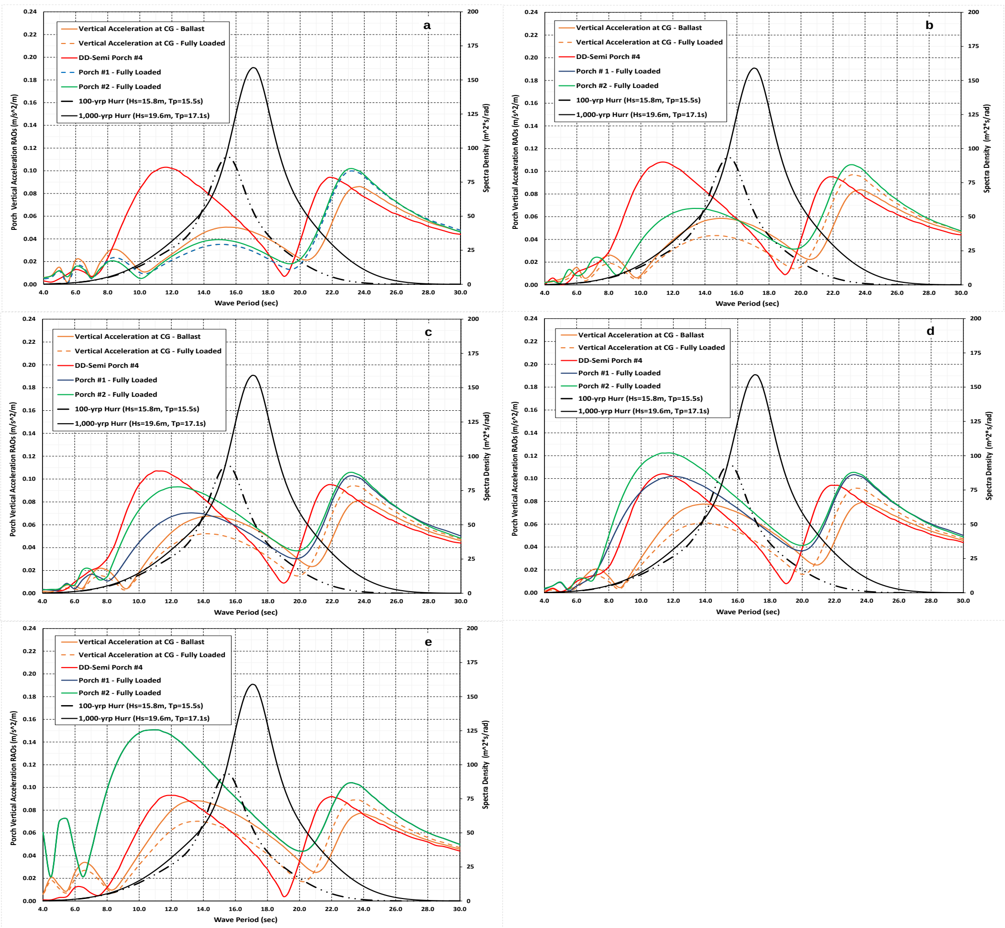


Fig. 21 The PVA RAOs: (a) 180 deg, (b) 150 deg, (c) 135 deg, (d) 120 deg and (e) 90 deg headings

Extreme WF heave motions of the SS-FPSO from 180 deg to 90 deg in 10-yrp, 100-yrp and 1,000-yrp hurricanes are summarized in Table 6 and plotted in Fig. 22.

From Table 6 and Fig. 22, a few findings are denoted as follows,

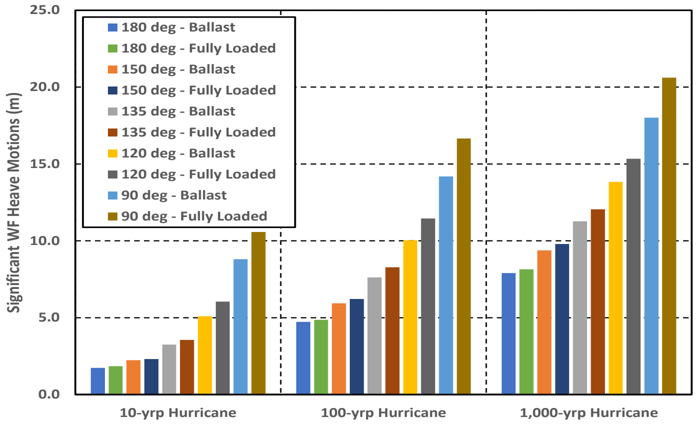


Fig. 22 Significant WF heave motions of the SS-FPSO in 10-yrp, 100-yrp and 1,000-yrp hurricanes

- Significant WF heave motions are sensitive to wave headings regardless of sea states and vessel loading conditions. Thus, it is essential to install turret system to weathervane from waves for harsh environmental conditions.
- For wave headings, 180 deg to 135 deg, there are above same extreme heaves in both ballast condition and fully loaded condition.
- For wave headings, 120 deg to 90 deg, extreme heave motions in fully loaded condition are getting worse than those in ballast condition.

5.4.1.2 Extreme WF heave motions of the eco-FPSO

Extreme WF heave motions of the eco-FPSO from 180 deg to 90 deg in 10-yrp, 100-yrp and 1,000-yrp hurricanes are summarized in Table 7 and displayed in Fig. 23.

From Table 7 and Fig. 23, a few observations are highlighted as follows,

- Significant WF heave motions are much less sensitive to wave headings with respect to those corresponding responses of the SS-FPSO regardless of sea states and vessel loading conditions. In addition, extreme values are considerably lower than those corresponding values especially in beam sea 90 deg heading.
- For all wave headings, 180 deg to 90 deg, extreme heave motions in fully loaded condition are lower than those corresponding responses in ballast condition.

Table 7 Extreme WF heave motions of the eco-FPSO

	Significant Wave-Frequency (WF) Heave Motions (m)					
	Ballast Condition			Fully Loaded Condition		
Headings	10-yrp	100-yrp	1,000-yrp	10-yrp	100-yrp	1,000-yrp
180 deg	1.64	3.86	6.05	1.17	2.97	5.45
150 deg	2.02	4.43	6.59	1.50	3.40	5.72
135 deg	2.42	5.02	7.18	1.85	3.89	6.09
120 deg	2.82	5.62	7.79	2.19	4.39	6.51
90 deg	3.22	6.21	8.42	2.53	4.89	6.97

Table 8 Extreme WF heave motions of the DD-Semi

	Significant WF Heave Motions (m)		
Headings	10-yrp	100-yrp	1,000-yrp
180 deg	3.03	5.38	7.55
150 deg	2.94	5.28	7.47
135 deg	2.91	5.24	7.44
120 deg	2.94	5.28	7.49
90 deg	3.03	5.38	7.55

5.4.1.3 Extreme WF heave motions of the DD-Semi

Extreme WF heave motions of the DD-Semi from 180 deg to 90 deg in 10-yrp, 100-yrp and 1,000-yrp hurricanes are summarized in Table 8 and illustrated in Fig. 24.

From Table 8 and Fig. 24, a few findings are presented as follows,

- Significant WF heave motions are almost same for all wave headings which indicate significant WF heave motions are nearly heading independent.
- For head sea 180 deg or beam sea 90 deg, extreme heave motions in 10-yrp, 100-yrp and 1,000-yrp hurricanes increase gradually for the DD-Semi.

5.4.1.4 Extreme WF heave motions of the SS-FPSO, eco-FPSO and DD-Semi

As discussed in 5.4.1.1, in general, extreme WF heave motions of the SS-FPSO in fully loaded condition are slightly worse or worse than those corresponding responses in ballast condition. Thus, extreme WF heave motions of the SS-FPSO in fully loaded condition are chosen for comparison in this section. As addressed in 5.4.1.2, extreme WF heave motions of the eco-FPSO in ballast condition are slightly worse or worse than those corresponding responses in fully loaded condition. Thus, extreme WF heave motions of the eco-FPSO in ballast condition are chosen for comparison in this section.

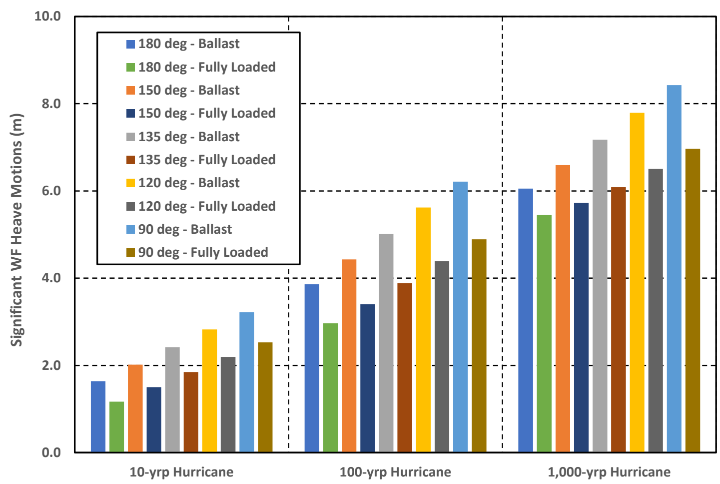


Fig. 23 Significant WF heave motions of the eco-FPSO in 10-yrp, 100-yrp and 1,000-yrp hurricanes

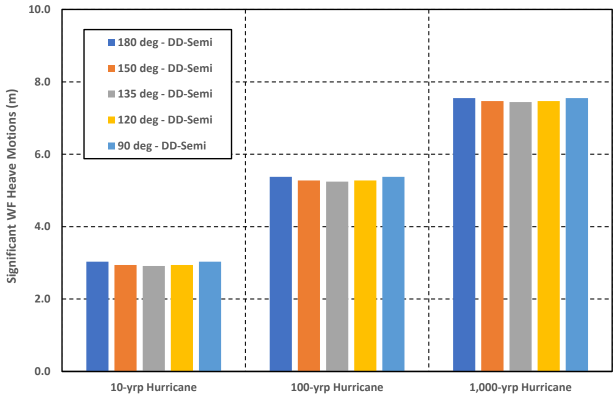


Fig. 24 Significant WF heave motions of the DD-Semi in 10-yrp, 100-yrp and 1,000-yrp hurricanes

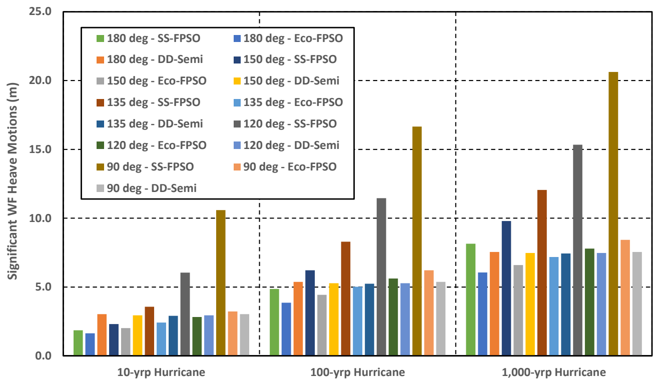


Fig. 25 Significant WF heave motions of the SS-FPSO, the eco-FPSO and the DD-Semi in 10-yrp, 100-yrp and 1,000-yrp hurricanes

Table 9 Extreme WF heave motions of the SS-FPSO, the eco-FPSO and DD-Semi

	Significant Wave-Frequency (WF) Heave Motions (m)								
	Fully Loaded Condition of the SS-FPSO			Ballast Condition of the eco-FPSO			The DD-Semi Platform		
Headings	10-yrp	100-yrp	1,000-yrp	10-yrp	100-yrp	1,000-yrp	10-yrp	100-yrp	1,000-yrp
180 deg	1.85	4.86	8.14	1.64	3.86	6.05	3.03	5.38	7.55
150 deg	2.31	6.22	9.80	2.02	4.43	6.59	2.94	5.28	7.47
135 deg	3.56	8.29	12.06	2.42	5.02	7.18	2.91	5.24	7.44
120 deg	6.05	11.45	15.33	2.82	5.62	7.79	2.94	5.28	7.49
90 deg	10.58	16.66	20.62	3.22	6.21	8.42	3.03	5.38	7.55

Extreme WF heave motions of the SS-FPSO, the eco-FPSO and the DD-Semi from 180 deg to 90 deg in 10-yrp, 100-yrp and 1,000-yrp hurricanes are summarized in Table 9 and illustrated in Fig. 25.

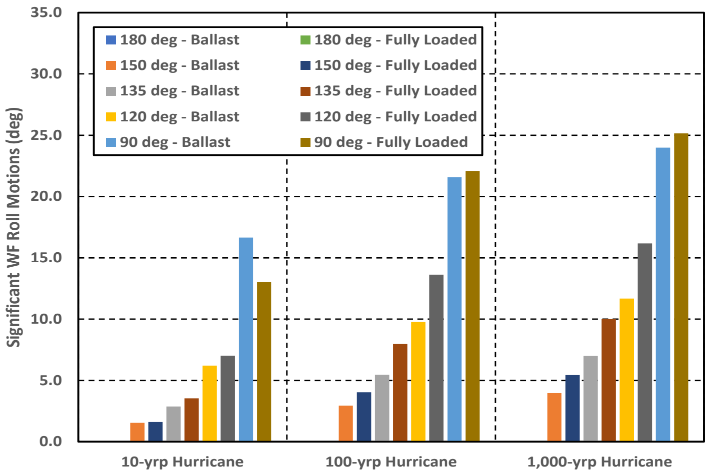


Fig. 26 Significant WF roll motions of the SS-FPSO in 10-yrp, 100-yrp and 1,000-yrp hurricanes

From Table 9 and Fig. 25, a few observations are highlighted as follows,

- The significant WF heave motions of the SS-FPSO, eco-FPSO and DD-Semi are similar,
  - In 10-yrp hurricane and headings from 180 deg to 135 deg,
  - In 100-yrp hurricane and headings from 180 deg to 150 deg,
  - In 1,000-yrp hurricane and 180 deg
- The differences of the motions of the SS-FPSO, eco-FPSO and DD-Semi are getting larger,
  - In 10-yrp hurricane and headings from 120 deg to 90 deg,
  - In 100-yrp hurricane and headings 135 deg to 90 deg,
  - In 1,000-yrp hurricane and headings from 150 deg to 90 deg

5.4.2 Extreme WF roll motions

5.4.2.1 Extreme WF roll motions of the SS-FPSO

Extreme WF roll motions of the SS-FPSO from 180 deg to 90 deg in 10-yrp, 100-yrp and 1,000-yrp hurricanes are summarized in Table 10 and displayed in Fig. 26.

From Table 10 and Fig. 26, a few findings are denoted as follows,

- Significant WF roll motions are sensitive to wave headings regardless of sea states and vessel loading conditions. Thus, similarly as observed from extreme heave motions, it is critical to equip turret system to weathervane from waves for harsh environmental conditions.
- For 10-yrp hurricane and headings from 150 deg to 120 deg, significant WF roll motions of the SS-FPSO in ballast condition and fully loaded condition are similar. For 90 deg, the differences between SS-FPSO in ballast condition and fully loaded condition are getting bigger. For wave headings, 180 deg to 135 deg, there are above same in both conditions.
- For 100-yrp and 1,000-yrp hurricanes, significant WF roll motions in fully loaded condition are slightly worse than those in ballast condition.

5.4.2.2 Extreme WF roll motions of the eco-FPSO

Extreme WF roll motions of the eco-FPSO from 180 deg to 90 deg in 10-yrp, 100-yrp and 1,000-yrp hurricanes are summarized in Table 11 and displayed in Fig. 27.

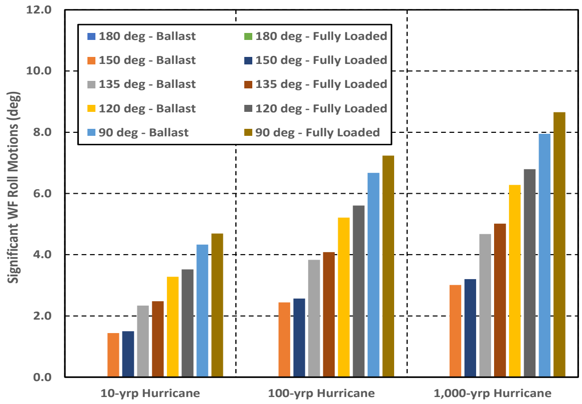


Fig. 27 Significant WF roll motions of the eco-FPSO in 10-yrp, 100-yrp and 1,000-yrp hurricanes

From Table 11 and Fig. 27, a few findings are given as follows,

- Significant WF roll motions are much less sensitive to wave headings with respect to those corresponding responses of the SS-FPSO regardless of sea states and vessel loading conditions. In addition, extreme values are considerably lower than those corresponding values especially in beam sea 90 deg heading.
- For all wave headings, 180 deg to 90 deg, extreme roll motions in fully loaded condition are higher than those corresponding responses in ballast condition.

Table 10 Extreme WF roll motions of the SS-FPSO

	Significant Wave-Frequency (WF) Roll Motions (deg)					
	Ballast Condition			Fully Loaded Condition		
Headings	10-yrp	100-yrp	1,000-yrp	10-yrp	100-yrp	1,000-yrp
180 deg	0.00	0.00	0.00	0.00	0.00	0.00
150 deg	1.54	2.95	3.97	1.61	4.04	5.44
135 deg	2.88	5.46	6.99	3.55	7.97	10.00
120 deg	6.21	9.76	11.68	7.01	13.63	16.18
90 deg	16.66	21.57	23.98	13.01	22.09	25.14

Table 11 Extreme WF roll motions of the eco-FPSO

	Significant Wave-Frequency (WF) Roll Motions (deg)					
	Ballast Condition			Fully Loaded Condition		
Headings	10-yrp	100-yrp	1,000-yrp	10-yrp	100-yrp	1,000-yrp
180 deg	0.00	0.00	0.00	0.00	0.00	0.00
150 deg	1.44	2.44	3.01	1.50	2.57	3.20
135 deg	2.34	3.83	4.68	2.48	4.08	5.01
120 deg	3.28	5.21	6.28	3.52	5.61	6.79
90 deg	4.33	6.67	7.95	4.69	7.24	8.66

Table 12 Extreme WF roll motions of the DD-Semi

	Significant Wave-Frequency (WF) Roll Motions (deg)		
Headings	10-yrp	100-yrp	1,000-yrp
180 deg	0.00	0.00	0.00
150 deg	1.24	1.73	1.97
135 deg	1.52	2.15	2.46
120 deg	1.57	2.27	2.62
90 deg	1.48	2.21	2.58

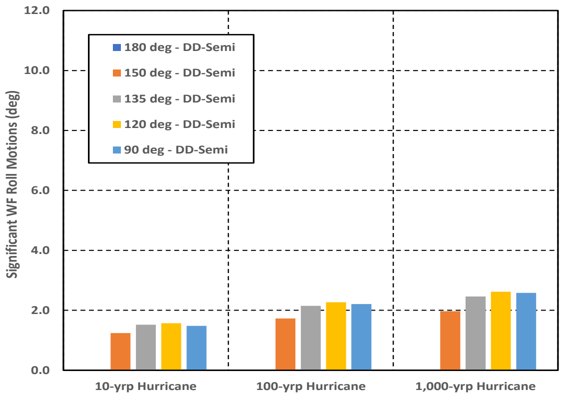


Fig. 28 Significant WF roll motions of the DD-Semi in 10-yrp, 100-yrp and 1,000-yrp hurricanes

5.4.2.3 Extreme WF roll motions of the DD-Semi

Extreme WF roll motions of the DD-Semi from 180 deg to 90 deg in 10-yrp, 100-yrp and 1,000-yrp hurricanes are summarized in Table 12 and illustrated in Fig. 28.

From Table 12 and Fig. 28, a few observations are presented as follows,

- Significant WF roll motions are almost same for all wave headings which indicate significant WF roll motions are nearly heading independent.
- From 150 deg to 90 deg headings, extreme roll motions in 10-yrp, 100-yrp and 1,000-yrp hurricanes vary gradually for the DD-Semi.

5.4.2.4 Extreme WF roll motions of the SS-FPSO, eco-FPSO and DD-Semi

As discussed in 5.4.2.1, in general, extreme WF roll motions of the SS-FPSO in fully loaded condition are slightly worse or worse than those corresponding responses in ballast condition. Thus, extreme WF roll motions of the SS-FPSO in fully loaded condition are chosen for comparison in this section. As addressed in 5.4.2.2, extreme WF roll motions of the eco-FPSO in fully loaded condition are slightly worse or worse than those corresponding responses in ballast condition. Thus, extreme WF roll motions of the eco-FPSO in fully loaded condition are chosen for comparison in this section.

Extreme WF roll motions of the SS-FPSO, the eco-FPSO and the DD-Semi from 180 deg to 90 deg in 10-yrp, 100-yrp and 1,000-yrp hurricanes are summarized in Table 13 and illustrated in Fig. 29.

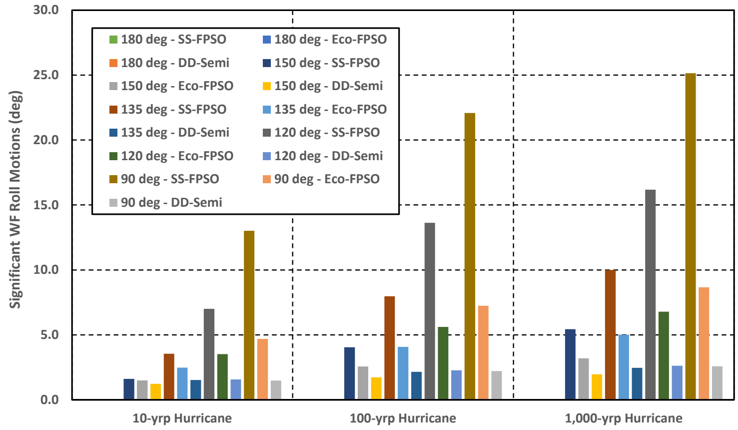


Fig. 29 Significant WF roll motions of the SS-FPSO, the eco-FPSO and the DD-Semi in 10-yrp, 100-yrp and 1,000-yrp hurricanes

Table 13 Extreme WF roll motions of the SS-FPSO, the eco-FPSO and DD-Semi

	Significant Wave-Frequency (WF) Roll Motions (deg)								
	Fully Loaded Condition of the SS-FPSO			Fully Loaded Condition of the eco-FPSO			The DD-Semi Platform		
Headings	10-yrp	100-yrp	1,000-yrp	10-yrp	100-yrp	1,000-yrp	10-yrp	100-yrp	1,000-yrp
180 deg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
150 deg	1.61	4.04	5.44	1.50	2.57	3.20	1.24	1.73	1.97
135 deg	3.55	7.97	10.00	2.48	4.08	5.01	1.52	2.15	2.46
120 deg	7.01	13.63	16.18	3.52	5.61	6.79	1.57	2.27	2.62
90 deg	13.01	22.09	25.14	4.69	7.24	8.66	1.48	2.21	2.58

Table 14 Extreme WF pitch motions of the SS-FPSO

	Significant Wave-Frequency (WF) Pitch Motions (deg)					
	Ballast Condition			Fully Loaded Condition		
Headings	10-yrp	100-yrp	1,000-yrp	10-yrp	100-yrp	1,000-yrp
180 deg	2.92	6.09	8.15	2.89	6.12	8.16
150 deg	3.43	6.38	8.19	3.56	6.55	8.34
135 deg	3.96	6.51	7.99	4.38	6.95	8.42
120 deg	4.20	6.12	7.17	4.93	6.89	7.95
90 deg	0.34	0.37	0.38	0.34	0.54	0.66

From Table 13 and Fig. 29, a few findings are presented as follows,

- For 150 deg heading, significant WF roll motions in 10-yrp hurricane are almost same for three hull forms, however, the differences among them are getting larger in 100-yrp hurricane and 1,000-yrp hurricane.

- For 135 deg to 90 deg, noticeable differences have been found even in 10-yrp hurricane, then, the trends start to magnify with sea states and variations of headings.
- In general, extreme roll motions of the eco-FPSO increase with sea states in 10-yrp, 100-yrp and 1,000-yrp hurricanes and heading variations from 150 deg to 90 deg, but the gradient of increases is much gentler than those observed in the SS-FPSO.
- Extreme roll motions of the eco-FPSO are slightly worse or worse than those responses of the DD-Semi revealing disadvantages of motion response characteristics for SCRs porch locations. To mitigate roll motion induced vertical motions at SCRs porch location, it must be arranged closely to the vessel center. A moonpool at the center of the vessel with 10m x 10m square opening (not shown in Fig. 3) which will slightly complicate the arrangement of storage tanks and topsides layout around the moonpool.

5.4.3 Extreme WF pitch motions

5.4.3.1 Extreme WF pitch motions of the SS-FPSO

Extreme WF heave motions of the SS-FPSO from 180 deg to 90 deg in 10-yrp, 100-yrp and 1,000-yrp hurricanes are summarized in Table 14 and plotted in Fig. 30.

From Table 14 and Fig. 30, a few observations are denoted as follows,

- Significant WF pitch motions are less sensitive to wave headings regardless of sea states and vessel loading conditions compared to significant WF heave motions and roll motions.
- For wave headings, 180 deg, 150 deg and 90 deg, there are above same extreme pitches in both ballast condition and fully loaded condition.
- For wave headings, 135 deg and 120 deg, extreme pitch motions in fully loaded condition are slightly worse than those in ballast condition.

5.4.3.2 Extreme WF pitch motions of the eco-FPSO

Extreme WF pitch motions of the eco-FPSO from 180 deg to 90 deg in 10-yrp, 100-yrp and 1,000-yrp hurricanes are summarized in Table 15 and displayed in Fig. 31.

From Table 15 and Fig. 31, a few observations are highlighted as follows,

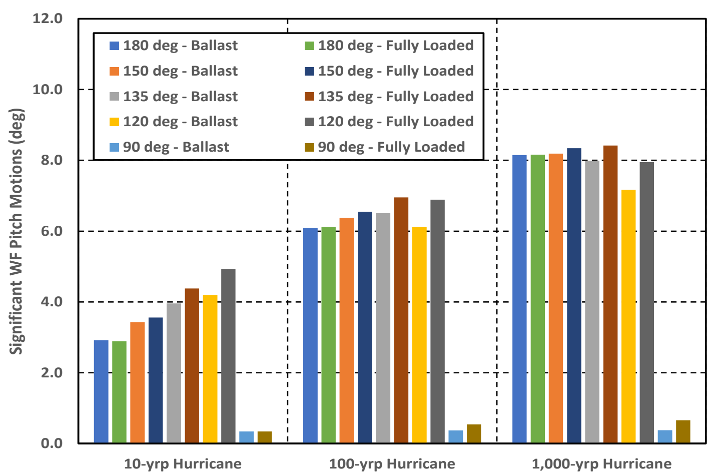


Fig. 30 Significant WF pitch motions of the SS-FPSO in 10-yrp, 100-yrp and 1,000-yrp hurricanes

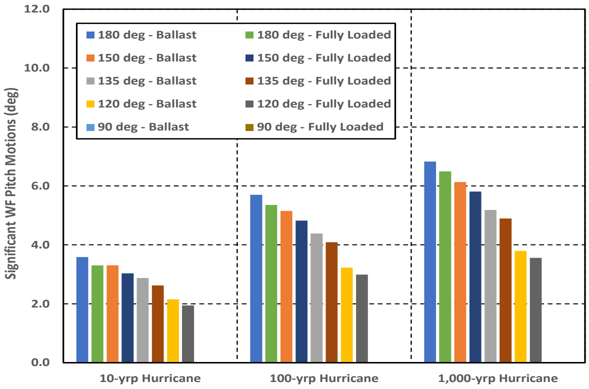


Fig. 31 Significant WF pitch motions of the eco-FPSO in 10-yrp, 100-yrp and 1,000-yrp hurricanes

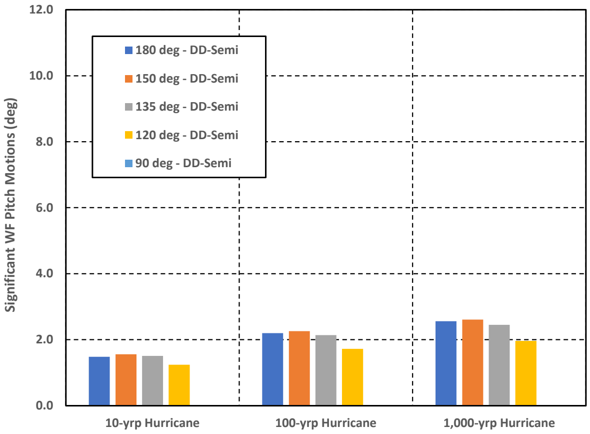


Fig. 32 Significant WF pitch motions of the DD-Semi in 10-yrp, 100-yrp and 1,000-yrp hurricanes

- Significant WF pitch motions are less sensitive to wave headings with respect to those corresponding responses of the SS-FPSO regardless of sea states and vessel loading conditions. In addition, extreme values in 100-yrp and 1,000-yrp hurricanes are lower than those corresponding values especially in head sea 180 deg heading.
- For all wave headings, 180 deg to 120 deg, extreme pitch motions in fully loaded condition are slightly lower than those corresponding responses in ballast condition.

5.4.3.3 Extreme WF pitch motions of the DD-Semi

Extreme WF pitch motions of the DD-Semi from 180 deg to 90 deg in 10-yrp, 100-yrp and 1,000-yrp hurricanes are summarized in Table 16 and illustrated in Fig. 32.

From Table 16 and Fig. 32, a few findings are presented as follows,

- Significant WF pitch motions are almost same for all wave headings which indicate significant WF pitch motions are nearly heading independent.
- From 180 deg to 120 deg headings, extreme pitch motions in 10-yrp, 100-yrp and 1,000-yrp hurricanes vary gradually for the DD-Semi.

Table 15 Extreme WF pitch motions of the eco-FPSO

	Significant Wave-Frequency (WF) Pitch Motions (deg)					
	Ballast Condition			Fully Loaded Condition		
Headings	10-yrp	100-yrp	1,000-yrp	10-yrp	100-yrp	1,000-yrp
180 deg	3.58	5.70	6.83	3.30	5.35	6.49
150 deg	3.31	5.15	6.13	3.03	4.82	5.81
135 deg	2.87	4.39	5.19	2.62	4.09	4.89
120 deg	2.15	3.23	3.79	1.95	2.99	3.56
90 deg	0.00	0.00	0.00	0.00	0.00	0.00

Table 16 Extreme WF pitch motions of the DD-Semi

	Significant Wave-Frequency (WF) Pitch Motions (deg)		
Headings	10-yrp	100-yrp	1,000-yrp
180 deg	1.48	2.20	2.56
150 deg	1.56	2.26	2.61
135 deg	1.51	2.14	2.45
120 deg	1.24	1.72	1.96
90 deg	0.00	0.00	0.00

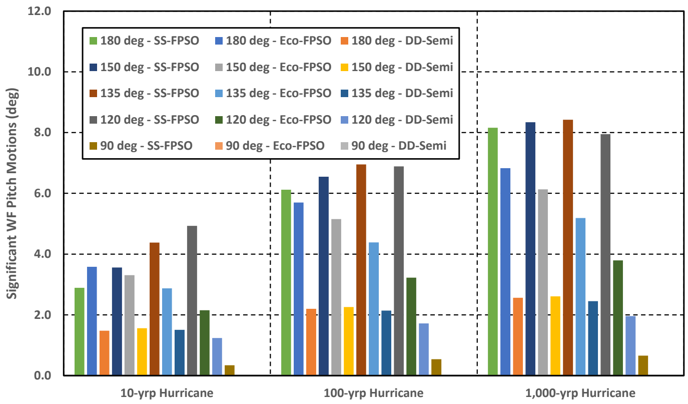


Fig. 33 Significant WF pitch motions of the SS-FPSO, the eco-FPSO and the DD-Semi in 10-yrp, 100-yrp and 1,000-yrp hurricanes

5.4.3.4 Extreme WF pitch motions of the SS-FPSO, eco-FPSO and DD-Semi

As discussed in 5.4.3.1, in general, extreme WF pitch motions of the SS-FPSO in fully loaded condition for 135 deg and 120 deg headings are slightly worse than those corresponding responses in ballast condition. Thus, extreme WF pitch motions of the SS-FPSO in fully loaded condition are chosen for comparison in this section. As addressed in 5.4.3.2, extreme WF pitch motions of the eco-FPSO in ballast condition are slightly worse than those corresponding responses in fully loaded condition. Thus, extreme WF pitch motions of the eco-FPSO in ballast condition are chosen for comparison in this section.

Table 17 Extreme WF pitch motions of the SS-FPSO, the eco-FPSO and DD-Semi

	Significant Wave-Frequency (WF) Pitch Motions (deg)								
	Fully Loaded Condition of the SS-FPSO			Fully Loaded Condition of the eco-FPSO			The DD-Semi Platform		
Headings	10-yrp	100-yrp	1,000-yrp	10-yrp	100-yrp	1,000-yrp	10-yrp	100-yrp	1,000-yrp
180 deg	2.89	6.12	8.16	3.58	5.70	6.83	1.48	2.20	2.56
150 deg	3.56	6.55	8.34	3.31	5.15	6.13	1.56	2.26	2.61
135 deg	4.38	6.95	8.42	2.87	4.39	5.19	1.51	2.14	2.45
120 deg	4.93	6.89	7.95	2.15	3.23	3.79	1.24	1.72	1.96
90 deg	0.34	0.54	0.66	0.00	0.00	0.00	0.00	0.00	0.00

Table 18 Extreme WF wave upwellings

	Significant Wave-Frequency Wave Upwellings (m)	
Sea States	eco-FPSO	DD-Semi
100-yrp Hurricane	19.2	16.7
1,000-yrp Hurricane	21.1	20.2

Extreme WF pitch motions of the SS-FPSO, the eco-FPSO and the DD-Semi from 180 deg to 90 deg in 10-yrp, 100-yrp and 1,000-yrp hurricanes are summarized in Table 17 and illustrated in Fig. 33.

From Table 17 and Fig. 33, a few findings are presented as follows,

- For all headings and all sea states, significant WF pitch motions are much better than those corresponding responses of the SS-FPSO and the eco-FPSO.
- For head sea 180 deg, significant WF pitch motions of the SS-FPSO in 10-yrp hurricane are slightly lower than that of the eco-FPSO. However, significant WF pitch motions of the SS-FPSO in 100-yrp hurricane and 1,000-yrp hurricane are slightly higher or higher than those of the eco-FPSO.
- For 150 deg to 120 deg, the differences of extreme pitch motions are becoming larger in same return period sea state and getting bigger with same heading but different sea states: 10-yrp, 100-yrp and 1,000-yrp hurricanes.
- Similarly, as observed in the WF roll motions, extreme pitch motions of the eco-FPSO are slightly worse or worse than those responses of the DD-Semi indicating unfavorable feature for SCRs porch locations which must be arranged closely to the vessel center. Normally, it requires a moonpool at the center of the vessel which will slightly complicate the arrangement of storage tanks and topside layout around the moonpool.

5.5 Extreme WF wave upwellings and minimum airgaps

5.5.1 General

To examine whether minimum airgap criteria had been satisfied for the eco-FPSO in 100-yrp and 1,000-yrp hurricanes, 11 points along vessel longitudinal as shown in Fig. 10 and screening study from heading sea 180 deg to 90 deg headings had been undertaken as stated in Zou (2020a) and critical location and critical heading had been identified and the corresponding wave upwelling

RAOs have been displayed in Fig. 11. Extreme WF wave upwellings of the eco-FPSO in 100-yrp and 1,000-yrp hurricanes are presented in Section 5.5.2. As a reference, extreme WF wave upwellings of the DD-Semi in 100-yrp and 1,000-yrp hurricanes are also included and compared in Section 5.5.2. Minimum airgaps of the eco-FPSO and the DD-Semi in 100-yrp and 1,000-yrp hurricanes are estimated, compared, and summarized in Section 5.5.3.

5.5.2 Extreme WF wave upwellings

Extreme WF wave upwellings of the eco-FPSO at AGP 6 in beam sea 90 deg heading and the DD-Semi at AGP 3 in 135 deg heading in 100-yrp and 1,000-yrp hurricanes are summarized in Table 18.

From Table 18, a few findings are highlighted as follows,

- For the eco-FPSO, as addressed in Section 4.2, since there is no crucial safety equipment installed on top of bulwark, the minimum airgap in 100-yrp hurricane is none-negative with respect to the top of bulwark which is different from that of the DD-Semi given in Section 4.1. Therefore, as described in Section 5.2.3, wave upwelling RAOs of the eco-FPSO have been tuned with respect to 1,000-yrp hurricane.
- For the DD-Semi, as presented in Section 4.1, the minimum airgap in 100-yrp hurricane is 1.5 m or below with respect to the top of column. Unlike the approach for the eco-FPSO, as addressed in Section 5.2.3, wave upwelling RAOs of the DD-Semi have been tuned with "balanced resultant" optimal with respect to both 100-yrp and 1,000-yrp hurricanes.
- Extreme WF wave upwellings of the DD-Semi are 2.8 m less in 100-yrp hurricane and 0.9 m less in 1,000-yrp hurricane than the corresponding responses of the eco-FPSO. Minimum airgaps of the DD-Semi and the eco-FPSO in 100-yrp and 1,000-yrp hurricanes are presented in Section 5.5.3

5.5.3 Minimum airgaps

Since minimum airgaps are resultant effects of platform/vessel mean pulling down due to mean vertical tension increase of moorings and risers at the mean offsets, mean vertical clearance decrease or increase depending on location of reference point and mean roll and pitch angles, extreme WF wave upwellings, low-frequency of roll and pitch induced vertical motions at the reference point and phase relationship among incident waves, platform/vessel heave motions and platform/vessel vertical motions induced by roll and pitch motions.

- From Fig. 3, the eco-FPSO hull configuration has much larger water plane area, larger blockage and no waves passing through hull as observed for the DD-Semi hull shown in Fig. 4. These hull characteristics have been mostly reflected in wave upwelling RAOs as shown in Fig. 11. There are other contributors affecting minimum airgaps which are described and highlighted in this section.
- As indicated in Zou (2020a), the coupled time domain analysis of the eco-FPSO including 16 moorings and 6 SCRs as shown in Fig. 5 had been undertaken. The coupled time domain analysis of the DD-Semi including moorings and risers had been carried out in a separate study. The mean platform/vessel pulling down at CG and mean rotation angles in 100-yrp hurricane and 1,000-yrp hurricane are extracted and summarized in Table 19.

Minimum airgaps of the DD-Semi and the eco-FPSO in 100-yrp and 1,000-yrp hurricanes are itemized and compared in Table 20. Final minimum airgaps shall be verified by wave basin model tests.

Table 19 The mean platform/vessel pulling downs at CG and mean rotations

	Mean Pulling downs at CG (m)		Mean Rotations (deg)	
Sea States	eco-FPSO	DD-Semi	eco-FPSO	DD-Semi
100-yrp Hurricane	-0.20	-0.75	2.80	1.85
1,000-yrp Hurricane	-0.50	-1.80	3.70	2.60

Table 20 Summary of minimum airgaps of the DD-Semi and the eco-FPSO

	Ballast Condition		Fully Loaded Condition	
	100-yrp	1,000-yrp	100-yrp	1,000-yrp
Critical Point	AGP #6 (0m, 48m)		AGP #3 (-26.4m, 26.4m)	
Still water clearance (m), see note 1	21.0	23.0	22.5	26.0
Clearance changed due to mean rotation (m)	2.35	3.10	-1.21	-1.69
Clearance at the mean position (m)	23.15	25.60	20.54	22.51
Maximum wave upwellings (m)	19.76	24.50	17.33	21.76
Minimum airgaps (m)	3.39	1.10	3.22	0.74
Required minimum airgaps (m)	≥0.0	≥0.0	≥1.5	≥0.0
Satisfied or not?	Yes	Yes	Yes	Yes

Table 21 Extreme WF PVDs and platform heave motions

	10-yrp Hurricane					100-yrp Hurricane					1,000-yrp Hurricane				
Headings	At CG	Porch 1	Porch 2	Porch 3	Porch 4	At CG	Porch 1	Porch 2	Porch 3	Porch 4	At CG	Porch 1	Porch 2	Porch 3	Porch 4
	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)
180 deg	3.03	3.15	3.15	3.34	3.34	5.38	5.46	5.46	5.65	5.65	7.55	7.65	7.65	7.86	7.86
150 deg	2.94	3.04	3.17	3.24	3.43	5.28	5.35	5.46	5.53	5.73	7.47	7.56	7.68	7.76	7.96
135 deg	2.91	2.99	3.16	3.16	3.40	5.24	5.29	5.45	5.45	5.71	7.44	7.51	7.68	7.68	7.94
120 deg	2.94	2.99	3.16	3.11	3.34	5.28	5.30	5.45	5.40	5.64	7.47	7.51	7.67	7.62	7.86
90 deg	3.03	3.03	3.13	3.03	3.13	5.38	5.38	5.44	5.38	5.44	7.55	7.55	7.63	7.55	7.63

5.6 Extreme WF porch vertical responses of the DD-Semi

5.6.1 Extreme WF PVDs

PVD RAOs as well as heave motion RAOs at CG of the DD-Semi have been presented in Section 5.3.3.1. Extreme WF PVDs as well as heave motions at CG of the DD-Semi in 10-yrp, 100-yrp and 1,000-yrp hurricanes from 180 deg to 90 deg are summarized in Table 21 and plotted in Fig. 34 respectively.

5.6.2 Extreme WF PVVs

PVV RAOs as well as heave velocity RAOs at CG of the DD-Semi have been presented in Section 5.3.3.2. Extreme WF PVVs as well as heave velocities at CG of the DD-Semi in 10-yrp, 100-yrp and 1,000-yrp hurricanes from 180 deg to 90 deg are summarized in Table 22 and plotted in Fig. 35 respectively.

5.6.3 Extreme WF PVAs

PVA RAOs as well as heave acceleration RAOs at CG of the DD-Semi have been presented in Section 5.3.3.3. Extreme WF PVAs as well as heave accelerations at CG of the DD-Semi in 10-yrp, 100-yrp and 1,000-yrp hurricanes from 180 deg to 90 deg are summarized in Table 23 and plotted in Fig. 36 respectively.

From Table 21 to Table 23 and Fig. 34 to Fig. 36, a few observations are summarized as follows,

- Variations of extreme WF vertical motions, velocities, accelerations at CG, porch 1 to porch 4 are small regardless of wave headings.

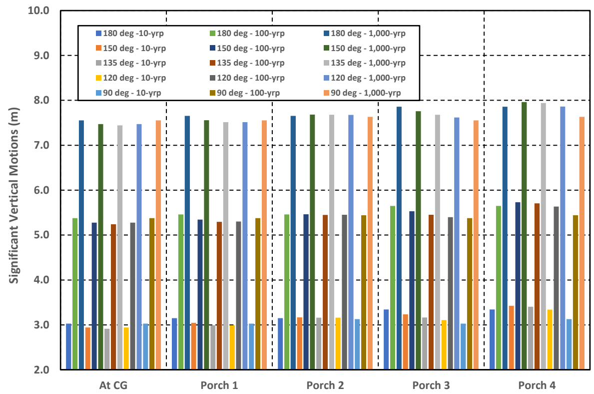


Fig. 34 Extreme WF PVDs and platform heave motions in 10-yrp,100-yrp and 1,000-yrp hurricanes

Table 22 Extreme WF PVVs and platform heave velocities

	10-yrp Hurricane					100-yrp Hurricane					1,000-yrp Hurricane				
Headings	At CG	Porch 1	Porch 2	Porch 3	Porch 4	At CG	Porch 1	Porch 2	Porch 3	Porch 4	At CG	Porch 1	Porch 2	Porch 3	Porch 4
	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)
180 deg	1.45	1.53	1.53	1.64	1.64	2.26	2.33	2.33	2.44	2.44	2.82	2.88	2.88	3.00	3.00
150 deg	1.40	1.47	1.55	1.58	1.69	2.21	2.26	2.33	2.37	2.49	2.77	2.82	2.90	2.94	3.05
135 deg	1.39	1.44	1.54	1.54	1.68	2.19	2.23	2.33	2.33	2.48	2.75	2.80	2.89	2.89	3.04
120 deg	1.40	1.44	1.54	1.51	1.64	2.21	2.23	2.33	2.30	2.44	2.77	2.80	2.89	2.86	3.00
90 deg	1.45	1.45	1.51	1.45	1.51	2.26	2.26	2.31	2.26	2.31	2.82	2.82	2.87	2.82	2.87

Table 23 Extreme WF PVAs and platform heave accelerations

	10-yrp Hurricane					100-yrp Hurricane					1,000-yrp Hurricane				
Headings	At CG	Porch 1	Porch 2	Porch 3	Porch 4	At CG	Porch 1	Porch 2	Porch 3	Porch 4	At CG	Porch 1	Porch 2	Porch 3	Porch 4
	(m/s^2)	(m/s^2)	(m/s^2)	(m/s^2)	(m/s^2)	(m/s^2)	(m/s^2)	(m/s^2)	(m/s^2)	(m/s^2)	(m/s^2)	(m/s^2)	(m/s^2)	(m/s^2)	(m/s^2)
180 deg	0.71	0.76	0.76	0.83	0.83	1.01	1.05	1.05	1.13	1.13	1.16	1.21	1.21	1.28	1.28
150 deg	0.69	0.73	0.73	0.80	0.87	0.98	1.02	1.02	1.09	1.16	1.13	1.17	1.17	1.25	1.32
135 deg	0.68	0.71	0.77	0.78	0.86	0.97	1.00	1.06	1.07	1.16	1.13	1.16	1.22	1.22	1.31
120 deg	0.69	0.71	0.77	0.75	0.84	0.98	1.00	1.06	1.04	1.13	1.13	1.15	1.22	1.19	1.28
90 deg	0.71	0.71	0.75	0.71	0.75	1.01	1.01	1.05	1.01	1.05	1.16	1.16	1.20	1.16	1.20

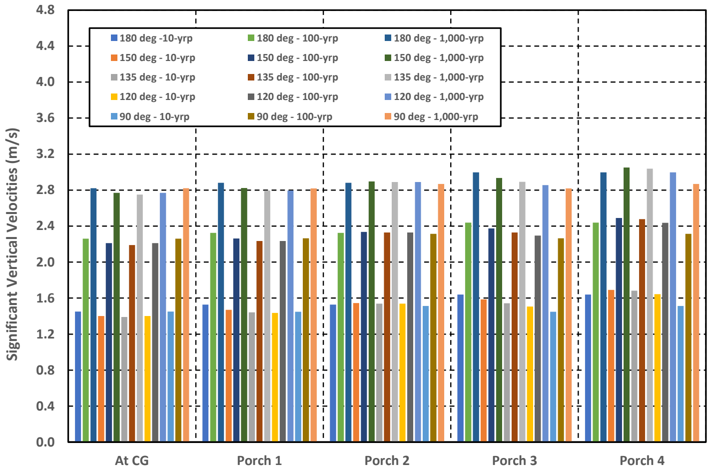


Fig. 35 Extreme WF PVVs and platform heave velocities in 10-yrp,100-yrp and 1,000-yrp hurricanes

- Among 5 locations, extreme WF PVDs, PVVs and PVAs at porch 4 are the highest or one of the highest. Thus, extreme WF PVDs, PVVs and PVAs at porch 4 are chosen as the representative values for the DD-Semi.

5.7 Extreme WF porch vertical responses of the eco-FPSO

5.7.1 Extreme WF PVDs

PVD RAOs as well as heave motion RAOs at vessel CG of the eco-FPSO in ballast and fully loaded conditions have been presented in Section 5.3.4.1. Extreme WF PVDs as well as heave motions at vessel CG of the eco-FPSO in ballast and fully loaded conditions in 10-yrp, 100-yrp and 1,000-yrp hurricanes from 180 deg to 90 deg are summarized in Table 24 and plotted in Fig. 37 respectively.

5.7.2 Extreme WF PPVs

PVV RAOs as well as heave velocity RAOs at vessel CG of the eco-FPSO have been presented in Section 5.3.4.2. Extreme WF PPVs as well as heave velocities at vessel CG of the eco-FPSO in

Table 24 Extreme WF PVDs and vessel heave motions

Headings	10-yrp Hurricane						100-yrp Hurricane						1,000-yrp Hurricane					
	Ballast Condition			Fully Loaded Condition			Ballast Condition			Fully Loaded Condition			Ballast Condition			Fully Loaded Condition		
	At CG	Porch 1	Porch 2	At CG	Porch 1	Porch 2	At CG	Porch 1	Porch 2	At CG	Porch 1	Porch 2	At CG	Porch 1	Porch 2	At CG	Porch 1	Porch 2
	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)
180 deg	1.64	1.70	1.80	1.17	1.28	1.33	3.86	3.81	4.16	2.97	2.95	3.26	6.05	5.91	6.42	5.45	5.31	5.81
150 deg	2.02	2.07	2.79	1.50	1.71	2.48	4.43	4.56	5.60	3.40	3.84	4.96	6.59	6.85	8.00	5.72	6.36	7.56
135 deg	2.42	2.82	3.59	1.85	2.60	3.37	5.02	5.63	6.69	3.89	5.09	6.20	7.18	8.00	9.16	6.09	7.60	8.81
120 deg	2.82	3.74	4.37	2.19	3.64	4.25	5.62	6.87	7.73	4.39	6.52	7.40	7.79	9.32	10.26	6.51	9.06	10.04
90 deg	3.22	4.98	4.98	2.53	5.00	5.00	6.21	8.50	8.50	4.89	8.37	8.37	8.42	11.08	11.08	6.97	11.02	11.02

Table 25 Extreme WF PPVs and vessel heave velocities

Headings	10-yrp Hurricane						100-yrp Hurricane						1,000-yrp Hurricane					
	Ballast Condition			Fully Loaded Condition			Ballast Condition			Fully Loaded Condition			Ballast Condition			Fully Loaded Condition		
	At CG	Porch 1	Porch 2	At CG	Porch 1	Porch 2	At CG	Porch 1	Porch 2	At CG	Porch 1	Porch 2	At CG	Porch 1	Porch 2	At CG	Porch 1	Porch 2
	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)
180 deg	0.72	0.78	0.80	0.53	0.60	0.59	1.51	1.52	1.63	1.11	1.14	1.23	2.11	2.09	2.26	1.73	1.72	1.88
150 deg	0.90	0.93	1.29	0.68	0.78	1.16	1.76	1.81	2.29	1.32	1.50	2.01	2.37	2.45	2.96	1.91	2.14	2.69
135 deg	1.09	1.31	1.70	0.84	1.22	1.61	2.03	2.31	2.81	1.55	2.08	2.60	2.65	2.98	3.51	2.11	2.74	3.30
120 deg	1.29	1.79	2.12	1.01	1.76	2.07	2.30	2.91	3.32	1.78	2.77	3.19	2.93	3.61	4.05	2.34	3.46	3.91
90 deg	1.49	2.46	2.46	1.17	2.49	2.49	2.57	3.73	3.73	2.02	3.70	3.70	3.22	4.48	4.48	2.57	4.43	4.43

ballast and fully loaded conditions in 10-yrp, 100-yrp and 1,000-yrp hurricanes from 180 deg to 90 deg are summarized in Table 25 and plotted in Fig. 38 respectively.

5.7.3 Extreme WF PVAs

PVA RAOs as well as heave acceleration RAOs at vessel CG of the eco-FPSO in ballast and fully loaded conditions have been presented in Section 5.3.4.3. Extreme WF PVAs as well as heave accelerations at vessel CG of the eco-FPSO in ballast and fully loaded conditions in 10-yrp, 100-yrp and 1,000-yrp hurricanes from 180 deg to 90 deg are summarized in Table 26 and plotted in Fig. 39 respectively.

From Table 24 to Table 26 and Fig. 37 to Fig. 39, a few findings are highlighted as follows,

- Extreme WF PVDs, PVVs, and PVAs as well as vessel heave motions, velocities, and accelerations of the eco-FPSO in Fully Loaded Conditions are lower or slightly lower than those corresponding responses in ballast condition in 10-yrp,100-yrp and 1,000-yrp hurricanes.

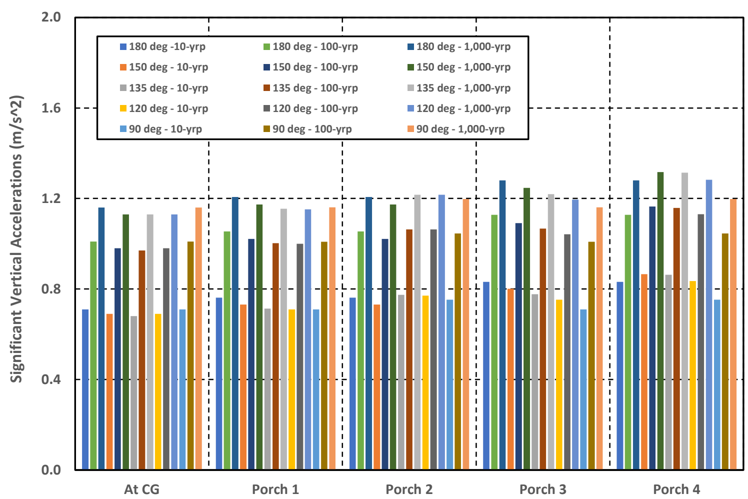


Fig. 36 Extreme WF PVAs and platform heave accelerations in 10-yrp,100-yrp and 1,000-yrp hurricanes

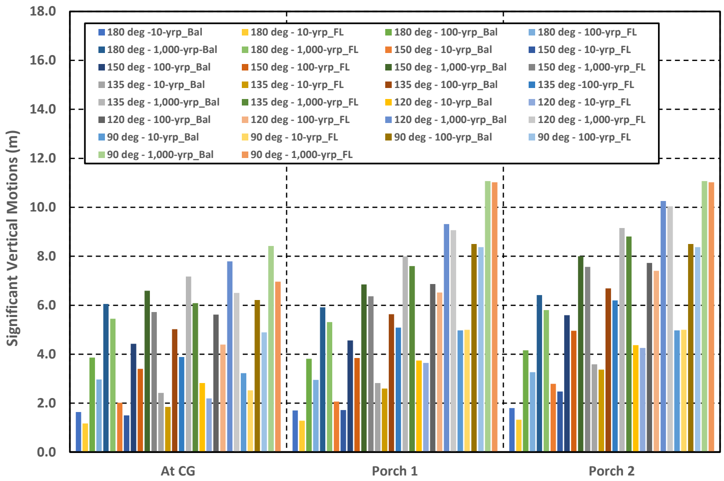


Fig. 37 Extreme WF PVDs and heave motions of the eco-FPSO in 10-yrp,100-yrp and 1,000-yrp hurricanes

Table 26 Extreme WF PVAs and vessel heave accelerations

Headings	10-yrp Hurricane						100-yrp Hurricane						1,000-yrp Hurricane					
	Ballast Condition			Fully Loaded Condition			Ballast Condition			Fully Loaded Condition			Ballast Condition			Fully Loaded Condition		
	At CG (m/s^2)	Porch 1 (m/s^2)	Porch 2 (m/s^2)	At CG (m/s^2)	Porch 1 (m/s^2)	Porch 2 (m/s^2)	At CG (m/s^2)	Porch 1 (m/s^2)	Porch 2 (m/s^2)	At CG (m/s^2)	Porch 1 (m/s^2)	Porch 2 (m/s^2)	At CG (m/s^2)	Porch 1 (m/s^2)	Porch 2 (m/s^2)	At CG (m/s^2)	Porch 1 (m/s^2)	Porch 2 (m/s^2)
180 deg	0.34	0.38	0.37	0.25	0.30	0.28	0.62	0.64	0.67	0.45	0.48	0.50	0.79	0.80	0.85	0.60	0.62	0.66
150 deg	0.42	0.43	0.62	0.31	0.36	0.56	0.73	0.75	0.98	0.54	0.62	0.86	0.91	0.94	1.18	0.69	0.79	1.05
135 deg	0.51	0.62	0.84	0.39	0.59	0.80	0.85	0.99	1.24	0.65	0.90	1.16	1.04	1.19	1.45	0.80	1.08	1.35
120 deg	0.61	0.89	1.07	0.48	0.88	1.05	0.98	1.30	1.52	0.76	1.26	1.47	1.17	1.51	1.74	0.91	1.45	1.68
90 deg	0.71	1.28	1.28	0.56	1.30	1.30	1.11	1.75	1.75	0.87	1.76	1.76	1.31	1.99	1.99	1.03	1.98	1.98

Table 27 Four extreme WF PVDs of the eco-FPSO vs extreme WF PVDs of the DD-Semi at porch 4

Headings	10-yrp Hurricane					100-yrp Hurricane					1,000-yrp Hurricane				
	DD-Semi	eco-FPSO				DD-Semi	eco-FPSO				DD-Semi	eco-FPSO			
	Porch 4	At CG_ Bal	At CG_ FL	Porch 1	Porch 2	Porch 4	At CG_ Bal	At CG_ FL	Porch 1	Porch 2	Porch 4	At CG_ Bal	At CG_ FL	Porch 1	Porch 2
	RP #1	RP #2	RP #3	RP #4	RP #5	RP #1	RP #2	RP #3	RP #4	RP #5	RP #1	RP #2	RP #3	RP #4	RP #5
	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)
180 deg	3.34	1.64	1.17	1.28	1.33	5.65	3.86	2.97	2.95	3.26	7.86	6.05	5.45	5.31	5.81
150 deg	3.43	2.02	1.50	1.71	2.48	5.73	4.43	3.40	3.84	4.96	7.96	6.59	5.72	6.36	7.56
135 deg	3.40	2.42	1.85	2.60	3.37	5.71	5.02	3.89	5.09	6.20	7.94	7.18	6.09	7.60	8.81
120 deg	3.34	2.82	2.19	3.64	4.25	5.64	5.62	4.39	6.52	7.40	7.86	7.79	6.51	9.06	10.04
90 deg	3.13	3.22	2.53	5.00	5.00	5.44	6.21	4.89	8.37	8.37	7.63	8.42	6.97	11.02	11.02

- Extreme WF PVDs, PVVs, and PVAs at porches 1 and 2 of the eco-FPSO in fully loaded conditions and vessel heave motions, velocities, and accelerations of the eco-FPSO in both ballast and fully loaded conditions have been selected for comparisons with those corresponding responses of the DD-Semi porch 4.

5.8 Extreme WF porch vertical responses: eco-FPSO vs DD-Semi

5.8.1 Comparisons of extreme PVDs: eco-FPSO vs DD-Semi

As discussed in Section 5.6.1, WF extreme PVDs of the DD-Semi at Porch 4 has been chosen as a measure, four representative PVDs of the eco-FPSO as indicated in Section 5.7.1 are directly compared with those corresponding responses of the DD-Semi at porch 4 and summarized in Table 27 and displayed in Fig. 40(a) to Fig. 40(c) respectively.

5.8.2 Comparisons of extreme PVVs: eco-FPSO vs DD-Semi

As discussed in Section 5.6.2, WF extreme PVVs of the DD-Semi at porch 4 has been chosen as a measure, four representative PVVs of the eco-FPSO as indicated in Section 5.7.2 are directly compared with those corresponding responses of the DD-Semi at porch 4 and summarized in Table 28 and displayed in Fig. 41(a) to Fig. 41(c) respectively.

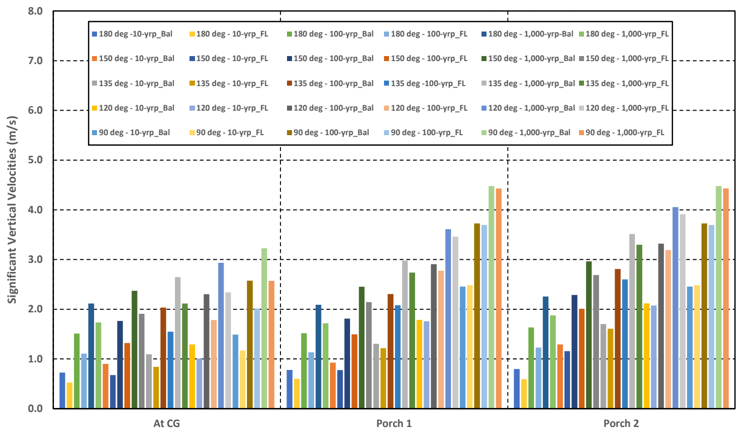


Fig. 38 Extreme WF PVVs and vessel heave velocities of the eco-FPSO in 10-yrp,100-yrp and 1,000-yrp hurricanes

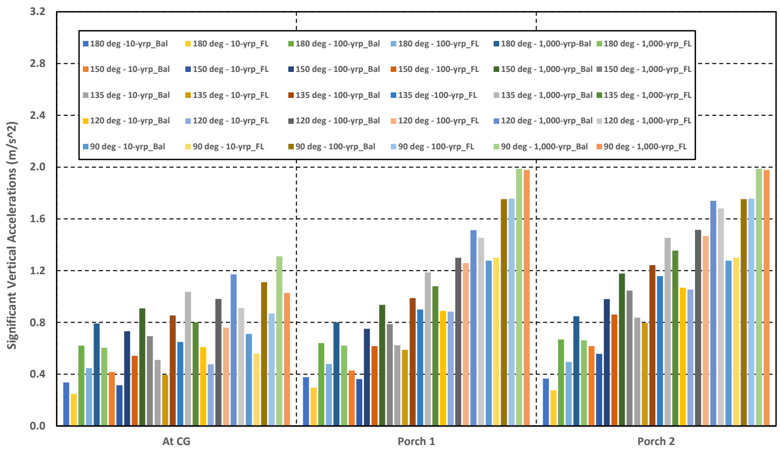
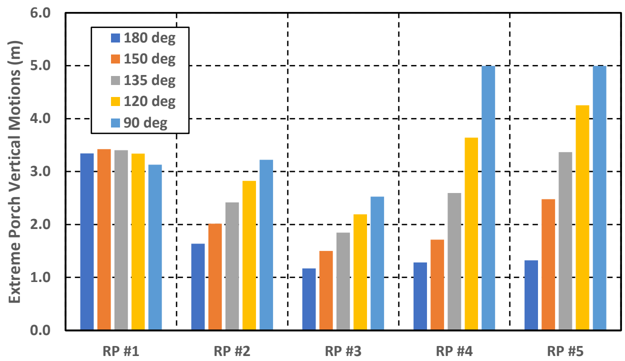
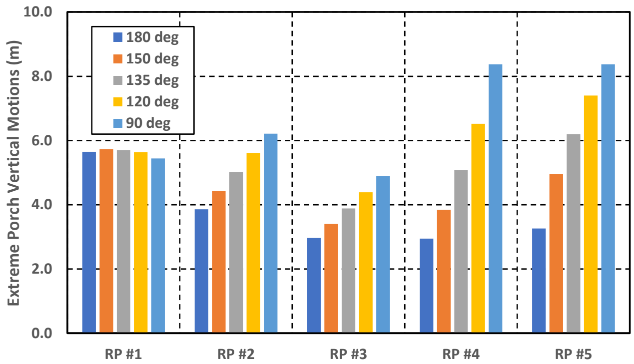


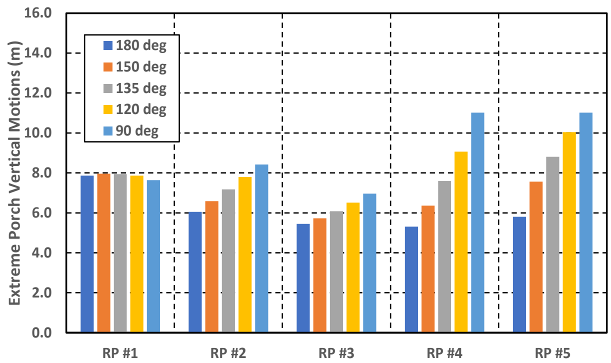
Fig. 39 Extreme WF PVAs and vessel heave accelerations of the eco-FPSO in 10-yrp,100-yrp and 1,000-yrp hurricanes



(a)



(b)



(c)

Fig. 40 (a) Extreme WF PVDs in 10-yrp Hurricane, (b) Extreme WF PVDs in 100-yrp Hurricane and (c) Extreme WF PVDs in 1,000-yrp hurricane

5.8.3 Comparisons of extreme PVAs: eco-FPSO vs DD-Semi

As discussed in Section 5.6.3, WF extreme PVAs of the DD-Semi at porch 4 has been chosen as a measure, four representative PVAs of the eco-FPSO as indicated in Section 5.7.3 are directly compared with those corresponding responses of the DD-Semi at porch 4 and summarized in Table 29 and displayed in Fig. 42(a) to Fig. 42(c) respectively.

From Table 27 to Table 29 and Fig. 40(a) to Fig. 40(c); Fig. 41(a) to Fig. 41(c); Fig. 42(a) to Fig. 42(c), a few observations are presented as follows, In 10-yrp hurricane, extreme WF PVDs, PVVs and PVAs of the eco-FPSO at vessel CG in ballast and fully loaded conditions are slightly lower or lower than those of the DD-Semi at porch 4 for all headings. While extreme WF PVDs, PVVs and PVAs of the eco-FSPO at porch 1 and porch 2 in fully loaded conditions are higher or considerably higher than those of the DD-Semi at porch 4 for 120 deg and 90 deg headings.

- In 100-yrp and 1,000-yrp hurricanes,
    - Extreme WF PVDs, PVVs and PVAs of the eco-FPSO at vessel CG in fully loaded condition are slightly lower or lower than those of the DD-Semi at porch 4 for all headings.
    - Extreme WF PVDs, PVVs and PVAs of the eco-FPSO at vessel CG in ballast condition are slightly lower than or equivalent to those of the DD-Semi at porch 4 for all headings except 90 deg heading. In beam sea, it is slightly higher than that of the DD-Semi at porch 4.
    - Extreme WF PVDs, PVVs and PVAs of the eco-FSPO at porch 1 and porch 2 in fully loaded conditions are higher or considerably higher than those of the DD-Semi at porch 4 for 120 deg and 90 deg headings. This deviating trend of the porch 2 starts at 135 deg heading in both 100-yrp and 1,000-yrp hurricanes.

Table 28 Four extreme WF PVVs of the eco-FPSO vs extreme WF PVVs of the DD-Semi at porch 4

	10-yrp Hurricane					100-yrp Hurricane					1,000-yrp Hurricane				
	DD-Semi	eco-FPSO				DD-Semi	eco-FPSO				DD-Semi	eco-FPSO			
Headings	Porch 4	At CG_ Bal	At CG_ FL	Porch 1	Porch 2	Porch 4	At CG_ Bal	At CG_ FL	Porch 1	Porch 2	Porch 4	At CG_ Bal	At CG_ FL	Porch 1	Porch 2
	RP #1	RP #2	RP #3	RP #4	RP #5	RP #1	RP #2	RP #3	RP #4	RP #5	RP #1	RP #2	RP #3	RP #4	RP #5
	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)
180 deg	1.64	0.72	0.53	0.60	0.59	2.44	1.51	1.11	1.14	1.23	3.00	2.11	1.73	1.72	1.88
150 deg	1.69	0.90	0.68	0.78	1.16	2.49	1.76	1.32	1.50	2.01	3.05	2.37	1.91	2.14	2.69
135 deg	1.68	1.09	0.84	1.22	1.61	2.48	2.03	1.55	2.08	2.60	3.04	2.65	2.11	2.74	3.30
120 deg	1.64	1.29	1.01	1.76	2.07	2.44	2.30	1.78	2.77	3.19	3.00	2.93	2.34	3.46	3.91
90 deg	1.51	1.49	1.17	2.49	2.49	2.31	2.57	2.02	3.70	3.70	2.87	3.22	2.57	4.43	4.43

Table 29 Four extreme WF PVAs of the eco-FPSO vs extreme WF PVAs of the DD-Semi at porch 4

	10-yrp Hurricane					100-yrp Hurricane					1,000-yrp Hurricane				
	DD-Semi	eco-FPSO				DD-Semi	eco-FPSO				DD-Semi	eco-FPSO			
Headings	Porch 4	At CG_ Bal	At CG_ FL	Porch 1	Porch 2	Porch 4	At CG_ Bal	At CG_ FL	Porch 1	Porch 2	Porch 4	At CG_ Bal	At CG_ FL	Porch 1	Porch 2
	RP #1	RP #2	RP #3	RP #4	RP #5	RP #1	RP #2	RP #3	RP #4	RP #5	RP #1	RP #2	RP #3	RP #4	RP #5
	(m/s^2)	(m/s^2)	(m/s^2)	(m/s^2)	(m/s^2)	(m/s^2)	(m/s^2)	(m/s^2)	(m/s^2)	(m/s^2)	(m/s^2)	(m/s^2)	(m/s^2)	(m/s^2)	(m/s^2)
180 deg	0.83	0.34	0.25	0.30	0.28	1.13	0.62	0.45	0.48	0.50	1.28	0.79	0.60	0.62	0.66
150 deg	0.87	0.42	0.31	0.36	0.56	1.16	0.73	0.54	0.62	0.86	1.32	0.91	0.69	0.79	1.05
135 deg	0.86	0.51	0.39	0.59	0.80	1.16	0.85	0.65	0.90	1.16	1.31	1.04	0.80	1.08	1.35
120 deg	0.84	0.61	0.48	0.88	1.05	1.13	0.98	0.76	1.26	1.47	1.28	1.17	0.91	1.45	1.68
90 deg	0.75	0.71	0.56	1.30	1.30	1.05	1.11	0.87	1.76	1.76	1.20	1.31	1.03	1.98	1.98

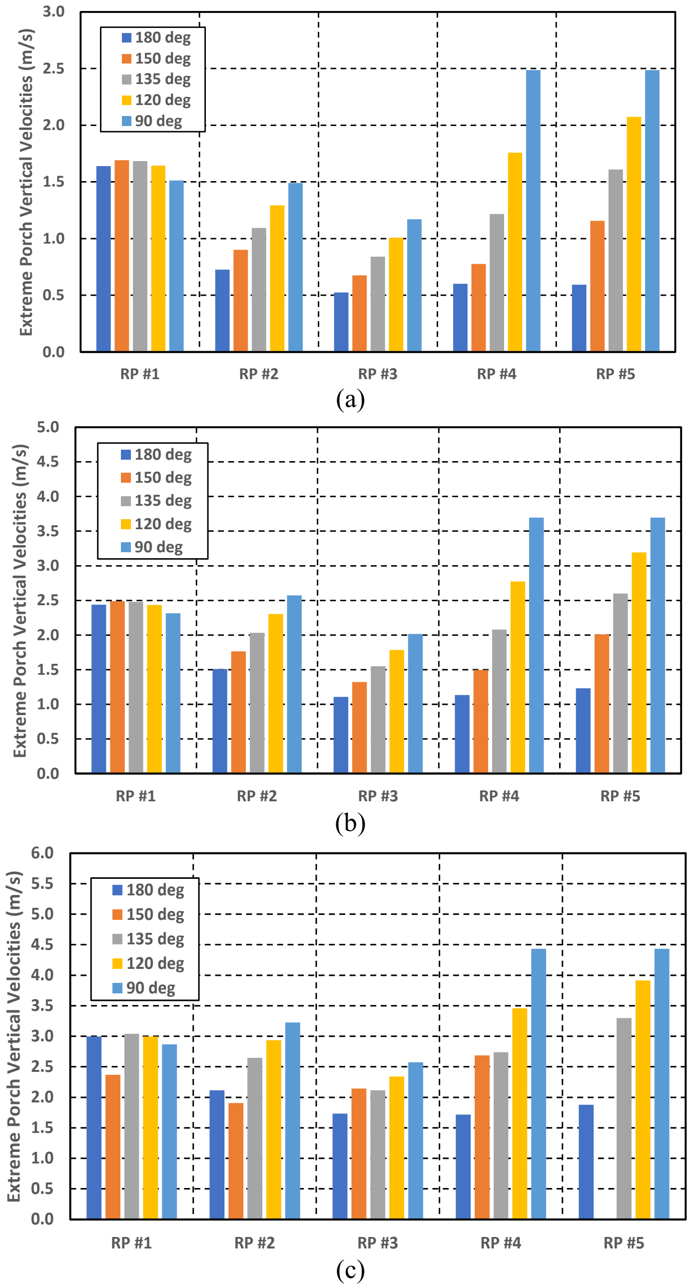
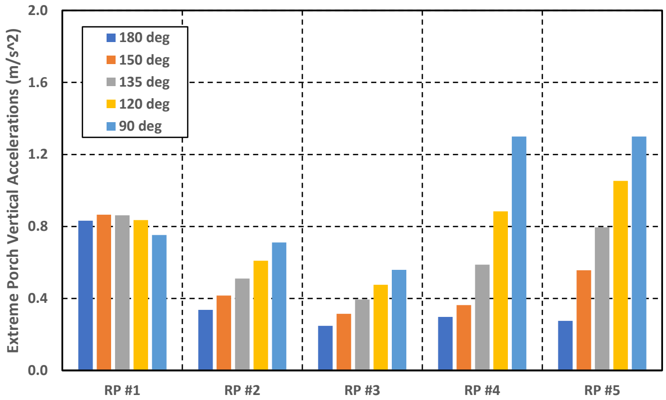


Fig. 41 (a) Extreme WF PVVs in 10-yrp hurricane, (b) Extreme WF PVVs in 100-yrp hurricane and (c) Extreme WF PVVs in 1,000-yrp hurricane

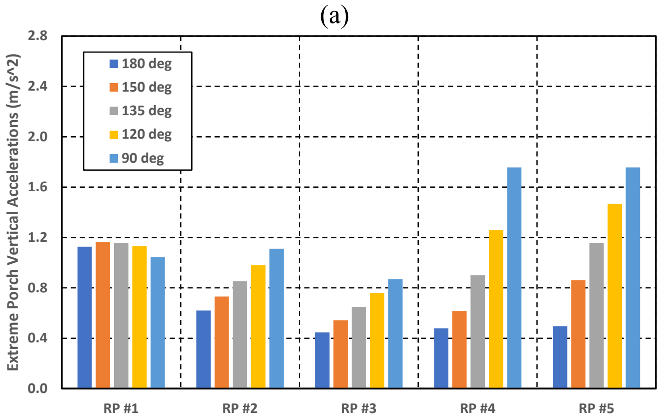
6. Conclusions

Dynamic response characteristics of an innovative turretless low motion FPSO in 10-yrp, 100-yrp and 1,000-yrp hurricanes in central GoM have been revealed, compared, and evaluated through

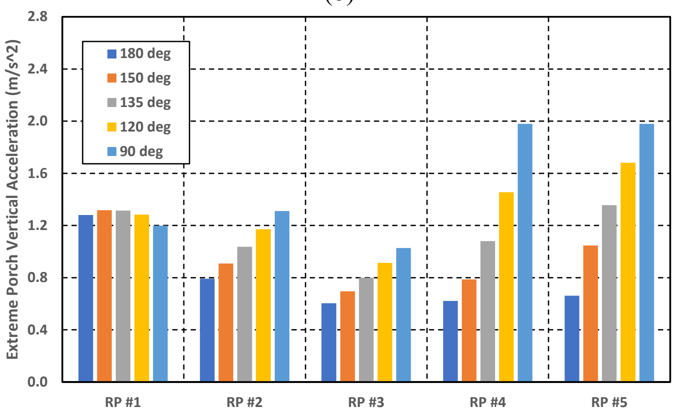
- Comparisons of the heave, roll and pitch motion RAOs and extreme WF heaves, rolls, and pitches among those corresponding responses of the SS-FPSO and the DD-Semi platform.
- Comparisons of wave upwelling RAOs and minimum airgaps with those corresponding responses of the DD-Semi platform



(a)



(b)



(c)

Fig. 42 (a) Extreme WF PVAs in 10-yrp hurricane, (b) Extreme WF PVAs in 100-yrp hurricane and (c) Extreme WF PVAs in 1,000-yrp hurricane

- Comparisons of PVD, PVV, and PVA RAOs and extreme WF PVDs, PVVs and PVAs with those corresponding responses of the DD-Semi platform.

Main conclusions on the proposed turretless low motion FPSO hull are drawn as follows:

- It has much improved motion characteristics than those of the SS-FPSO hull and offers equivalent motion features of the DD-Semi.
- It appears equivalent wave upwelling RAOs even in the beam sea as the wave upwelling RAOs in critical heading of the DD-Semi.
- It offers equivalent PVD, PVV and PVA RAOs and extreme WF PVDs, PVVs and PVAs at the moonpool near vessel center with respect to those corresponding responses of the DD-Semi.

Major recommendations on the proposed turretless low motion FPSO hull are given below,

- Original locations for SCRs porches of the eco-FPSO were considered to install outside of base tank along the longitudinal direction as illustrated in Fig. 12. The advantages of this arrangement are easy for SCRs pull-in operations and layouts of storage tank arrangement and topsides. However, they are feasible only for the field with strong directional sea states by aligning the beam sea with the direction of the most benign sea state. The robust locations for SCRs porches of the eco-FPSO are arranged at the moonpool. Thus, layouts of storage tanks and topsides are needed to be updated. These changes can be accommodated in the next phase development.
- The recent advancements of mooring hardware, no winches on deck, no chain locker and no on-board chain haven't been employed and factored into this study. However, these advancements will be employed to optimize design in the next phase development.
- Physical wave basin model tests are deemed to be necessary to verify and validate dynamic responses of the eco-FPSO presented in this paper. Model test correlation analysis will provide good indications for the next phase development.

Acknowledgments

The author would like to acknowledge for valuable contributions from my colleagues, special thanks go to Mr. Dongxing Jia for his important contributions on global loading and various challenging aspects.

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Nomenclature

Alphabets	
AFT	The Rearmost Part of the Vessel
AGP	Airgap Point
API	American Petroleum Institute
Bal	Ballast Condition
bbl	Barrel or barrels
CAPEX	Capital Expenditure
CG	Central Gravity
deg	Degree
DD-Semi	Deep Draft Semi-Submersible Platform
DOE	Department of Energy
Eco-FPSO	Economical Floating Production Storage and Offloading
ESDU	The Engineering Science Data Unit - Wind Spectrum Parameterization for Describing the Characteristics of Hurricane Winds Offshore
FL	Fully Loaded Condition
FPSO	Floating Production Storage and Offloading
FWD	The most Forward Part of the Vessel
GOM	Gulf of Mexico
LCCA	Life-Cycle Cost Analysis
MWL	Mean Water Level
OPEX	Operational Expenditure
PVA	Porch Vertical Acceleration
PVD	Porch Vertical Displacement
PVV	Porch Vertical Velocity
RAO	Response Amplitude Operators
RPSEA	Research Partnership to Secure Energy for America
SCRs	Steel Catenary Risers
SS-FPSO	Ship Shaped Floating Production Storage and Offloading
VCG	Vertical Central Gravity
WF	Wave-Frequency
yrp	Year Return Period