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Numerical and experimental investigation on the global performance of a novel design of a Low Motion FPSO

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Abstract. Floating Production Storage and Offloading (FPSO) units have the advantages of their ability to provide storage and offloading capabilities which are not available in other types of floating production systems. In addition, FPSOs also provide a large deck area and substantial topsides payload capacity. They are in use in a variety of water depths and environments around the world. It is a good solution for offshore oil and gas development in fields where there is lack of an export pipeline system to shore. However due to their inherently high motions in waves, they are limited in the types of risers they can host. The Low Motion FPSO (LM-FPSO) is a novel design that is developed to maintain the advantages of the conventional FPSOs while offering significantly lower motion responses. The LM-FPSO design generally consists of a box-shape hull with large storage capacity, a free-hanging solid ballast tank (SBT) located certain distance below the hull keel, a few groups of tendons arranged to connect the SBT to the hull, a mooring system for station keeping, and a riser system. The addition of SBT to the floater results in a significant increase in heave, roll and pitch natural periods, mainly through the mass and added mass of the SBT, which significantly reduces motions in the wave frequency range. Model tests were performed at the Korea Research Institute of Ships & Ocean Engineering (KRISO) in the fall of 2016. An analytical model of the basin model (MOM) was created in Orcaflex and calibrated against the basin-model. Good agreement is achieved between global performance results from MOM's predictions and basin model measurements. The model test measurements have further verified the superior motion response of LM-FPSO. In this paper, numerical results are presented to demonstrate the comparison and correlation of the MOM results with model test measurements. The verification of the superior motion response through model test measurements is also presented in this paper.

Keywords: wave basin test; Low Motion FPSO (LM-FPSO); global performance analysis

1. Introduction

Floating Production Storage and Offloading (FPSO) platforms provide crude oil storage, have plenty of deck area for topside and facilities, and are suitable for large topside payload, variety of

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water depths and environmental conditions. While there are currently approximately 180 FPSOs in operation worldwide, which is significantly more than the number of the other types of floating production systems combined, the motion of FPSOs is a major disadvantage and limits its application. The FPSO's heave/roll/pitch natural periods are usually in the wave frequency range (10s ~ 20s). The wave energy can induce significant heave, roll and pitch motions. Therefore, the FPSO cannot support dry tree applications or drilling and completion operation. In harsh or multi-directional environments, FPSOs typically require turret mooring system which adds high Capital Expenditure (CAPEX) and Operating Expenses (OPEX) to the project development. The high motion responses impair the platform habitability and helicopter operability. Crew members can get seasick which reduces productivity and increases the risk of injury.

Various researches have been performed to reduce the motion of FPSs. Na *et al.* (2002) designed a bilge keel to reduce the FPSO's roll motion. Thiagarajan *et al*. (1999) investigated the effects of turret mooring location on the FPSO's heave motion. Some other researchers focused on developing new design of floaters to provide better motion. Mansour *et al.* (2009, 2010, 2011, 2013, 2013, 2014, 2014) developed a Free-Hanging Solid Ballast (FHSB) semi-submersible and a Damper Chamber Column (DCC) semi-submersible which have good motion to support dry trees. Kim et al. (2008) studied the motion behavior of a Deep-Draft Semi-Submersible FLNG. Ha *et al*. (2002) investigated the motion of a LNG-ship with moonpool and bilge step at bottom. Khaw *et al*. (2005) designed a new mono-hull FPSO. Matsumoto *et al.* (2008) introduced the effects from appendages on the vertical motion of mono-column platform. Goncalves e*t al*. (2009, 2010) developed the MPSO (monocolumn production storage and offloading system) concept, which is a floating unit based on a monocolumn with a moonpool, to reduce the motions.

The Low Motion FPSO (LM-FPSO) is a novel design that not only maintains the advantages brought by conventional FPSO floaters, such as hull storage capacity, large deck area, high payload capacity, etc., but also offers superior motion and stability characteristics. The LM-FPSO design generally consists of a box-shaped FPSO hull, solid ballast tank (SBT) positioned a certain distance below the hull keel and connected to it through multiple groups of tendons. The hull is moored in-place through a conventional mooring system. Riser systems are conventionally connected to the hull. The hull and SBT are connected together by means of tendons. Each tendon is designed as a single element so that no offshore assembling is needed. The tendon has the same composition as the traditional design. The hull structure is a traditional stiffened plate type structure with easy fabrication. The hull footprint can be a square or a rectangular shape. The LM-FPSO offers superior motion response through the in-water weight and added mass of the SBT. Its heave, roll and pitch natural periods can be easily adjusted to be long enough to avoid resonant response periods in the wave frequency range, which also results in very low overall motion responses in waves. The superior motion enables the LM-FPSO to support dry tree applications and perform the drilling and completion operations from the floaters, resulting in significant CAPEX and OPEX savings compared to other development concepts (Mansour et al. 2017). The low motion response also makes the LM-FPSO a suitable host for low cost and robust Steel Catenary Risers (SCRs).

The SBT's dry weight (weight is air) is designed to be larger than its displacement. It is hung below the hull by tendons. The SBT's wet weight (dry weight – displacement) causes the pretension in tendons. With the same SBT size, the SBT's displacement keeps constant and larger SBT dry weight causes larger tendon pretension. When the tendon is in tension, the hull's vertical motion can push the tendon top and the tendon bottom can push the SBT. Due to the high axial stiffness of tendons, the hull and SBT's heave, roll and pitch motions are coupled together. When the tendon bottom loses tension, the tendon can slide downward in the tendon bottom receptacle. In this situation the tendon can't act on SBT so that the hull and SBT are decoupled. The dry weight of the SBT is designed such that the tendon's pretension is large enough to make the tendon always keep in tension in extreme environments and ensure fully coupling in the heave, roll and pitch directions between the hull and the SBT, resulting in the hull and the SBT acting as a unified system.

The typical LM-FPSO design is shown in Fig. 1.

The performance of LM-FPSO design has been extensively studied by numerical simulation in previous work (Mansour *et al.* 2015, 2017, Zuccolo *et al.* 2016, Peng *et al*. 2018, Sung *et al*. 2016, Song *et al*. 2017). The previous researches verified the superior motion response of the LM-FPSO in wet or dry tree applications, in harsh and/or swell environments, and in shallow or deep water depths.

In order to further verify the motion performance from the numerical simulations, a scale-model test was performed at the Korea Research Institute of Ships & Ocean Engineering (KRISO) model test facility in the fall of 2016. A numerical model was created in Orcaflex to represent the basin model. The LM-FPSO's performance results from the wave basin model test and the numerical simulations are compared and presented in this paper.

2. LM-FPSO model description

2.1 Prototype model description

The LM-FPSO used for this study targets for the Western Australia offshore condition. The water depth at the model location is 250 m. The 100yr and 10,000yr environmental conditions for this location are listed in Table 1.

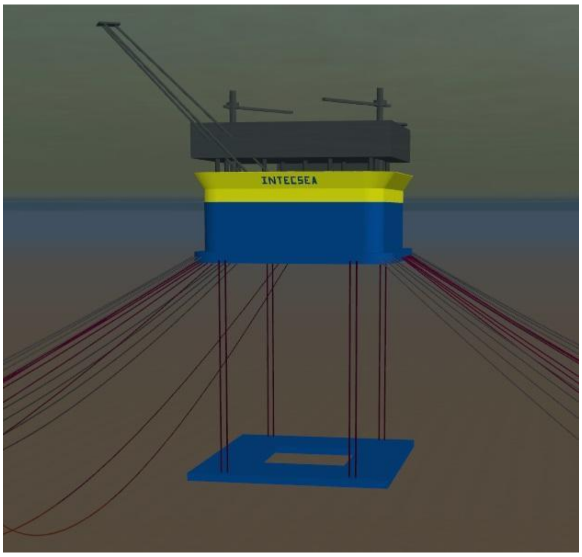


Fig. 1 Typical LM-FPSO

Table 1 100yr and 10,000yr Environmental Conditions for the Study Location

	Unit	100yr	10,000yr
Significant Wave Height (Hs)	(m)	6.9	10.6
Wave Peak Period (Tp)	(s)	10.0	11.7
Wave Shape Factor (γ)		2.0	2.0
1-hr Mean Wind Speed	(m/s)	32.0	55.0
Surface Current Speed	(m/s)	1.2	1.78

The LM-FPSO in this study consists of hull, SBT, tendon system, mooring system and SCR system. The hull main section is a box-shape with corner radii. The top part of the hull flares out to reduce the green water on top of the hull in extreme conditions. The bottom part of the hull is extended out of the main body as a skirt to provide additional added mass and damping as well as facilitate the SCR installation. The SBT has a rectangular footprint with a center opening. There are a total of 16 chain-wire-chain mooring lines for station-keeping and 14 SCRs for hydrocarbon production and export. The hull and SBT are connected by 8 tendons, 2 at each corner. The main particulars of LM-FPSO prototype model are presented in Table 2.

Table 2 Main Particulars of LM-FPSO Wave Basin Model (Prototype Scale)

Item	Unit	Value
Main Hull Section (L x W x H)	(m)	85.6 x 85.6 x 39.0
Hull Corner Radius	(m)	8.6
Hull Draft	(m)	28.0
Hull External Skirt at Keel (W x H)	(m)	5.0 x 5.0
Hull Skirt Corner Radius	(m)	13.6
Hull Mass	(MT)	35,422
Topside Mass	(MT)	44,504
SBT Section (L x W x H)	(m)	107.8 x 95.6 x 3.7
SBT Center Opening (L x W)	(m)	44.3 x 44.3
SBT Mass (including the Ballast)	(MT)	29,419
No. of Mooring Lines/Tendons/SCRs	/	16/8/14
No. of Mooring Lines	/	16
Mooring Line Type		Platform Chain-Wire-Anchor Chain
Mooring Line Component Nominal Diameter (Platform Chain / Wire / Anchor Chain)	(mm)	167 / 147.5 / 171
Mooring Line Component Length (Platform Chain / Wire / Anchor Chain)	(m)	40 / 330 / 1330
No. of Tendons		8
Tendon OD/ID	(m)	0.813/0.747
Tendon Length	(m)	100
SCR Types		22” Gas Export Riser / 14” Production Riser / 6” MEG Riser

2.2 Wave basin model description

1:60 model-scale was used in the model test. The selection of the model scale ensures sufficiently large model that would yield model responses representative of the prototype, less sensitive to scaling effects, has minimum effects from tank facility walls and floor, has minimum wave reflection effects from the end boundary of the tank and provides reliable reproduction of the desired wave spectra.

The mooring system for the prototype LM-FPSO is composed of sixteen chain-wire-chain mooring lines. Due to the horizontal and vertical space constraints in the wave tank facility, a truncated equivalent mooring system was designed. The equivalent (truncated) mooring system provided appropriate system restoring forces and moments to the scaled model. Fairlead connection coordinates remained the same as prototype model.

The riser system for the prototype LM-FPSO is composed by fourteen SCRs and seven umbilical lines. A truncated equivalent riser system was designed in the model test. SCRs and umbilical lines were lumped into fewer lines. Lumped and truncated system preserved the static properties of the prototype model and provided appropriate system restoring forces and moments to the scaled model.

The tendon model used in the model test matched prototype's hydrodynamic properties and tendon stiffness. Tendons were modeled in the basin without truncation or lumping. A spring was installed at the bottom of each tendon to provide the equivalent stiffness.

2.3 Numerical model of the basin model (MOM) description

Orcaflex is an industry standard software used extensively in the offshore oil and gas field, and was used in this study to generate and produce the numerical predictions of the MOM using fully coupled analysis in time domain. The hydrodynamic coefficients used in the MOM are calculated by WAMIT 2-body analysis, which included the hydrodynamic interaction between the hull and the SBT. Full Quadratic Transfer Functions (QTFs) are used to represent the second order response of the LM-FPSO. Morrison members are used in Orcaflex to represent the viscous load on the hull and SBT.

Model test calibrated wave Hs and Tp were used in MOM. The calibrated basin current profile was applied in the MOM and the initial hull horizontal drag for Morrison members was modified to tune LM-FPSO surge/sway offsets against the measured model test offsets in this condition. NPD wind spectrum was applied to MOM and “wind and current only” basin tests were used to tune hull wind force coefficients in the Orcaflex MOM in surge/sway directions.

The same lumped/truncated mooring and riser systems as in the basin model are modeled in Orcaflex MOM.

3. Comparison of numerical and experimental results

3.1 Static offset curves comparison

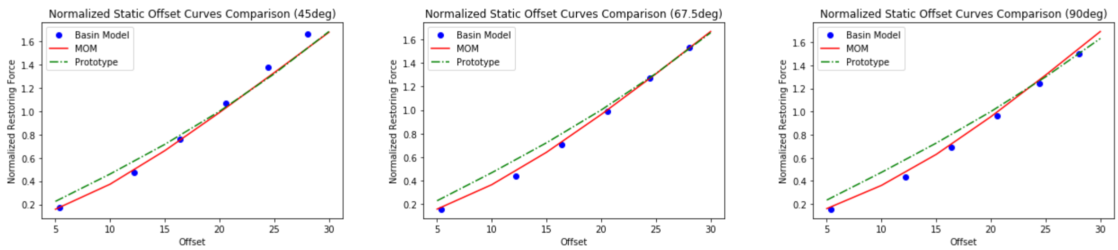
Static offset tests are performed in three directions: quartering (45 deg), orthogonal (90 deg) and in-between (67.5 deg) headings in the basin to verify that the basin model mooring and riser system lead to similar global restoring stiffness and mooring/riser line pretension versus offset as those in the prototype design. The static offset curves from basin model were compared to corresponding curves from the Orcaflex numerical Prototype model as well as MOM. Excellent agreement is observed in the predicted offset range of interest. The normalized static offset curves comparison is shown in Fig. 2.

3.2 Decay tests

6 degrees-of-freedom (DOF) motion decay tests are performed in the basin to verify the basin model natural periods and identify the system damping in these directions. The results from these tests are compared to corresponding decay test results from Orcaflex Prototype and MOM numerical tests in Table 3. It can be seen that MOM natural periods agrees well with model test results with a maximum difference of 8%, except for yaw where a difference of 12% is observed. The natural periods are very close to the prototype periods indicating that the basin model and the MOM provide good representation of the prototype. It is also worth to mention that the LM-FPSO's heave natural period is almost 20s, which is far from the 10,000yr wave peak period (11.7s) in the target area. The roll/pitch natural periods are even higher. Therefore, LM-FPSO's wave frequency motions are expected to be much smaller than the conventional FPSO design.

3.3 White noise and regular wave tests

White noise and regular tests have been performed in the basin and results have been compared to numerical predictions from Orcaflex Prototype time domain runs. The purpose of these tests is to generate and compare six DOFs motion RAOs and tendon top/bottom tension RAOs. The tests have been carried out with no wind and current effects.

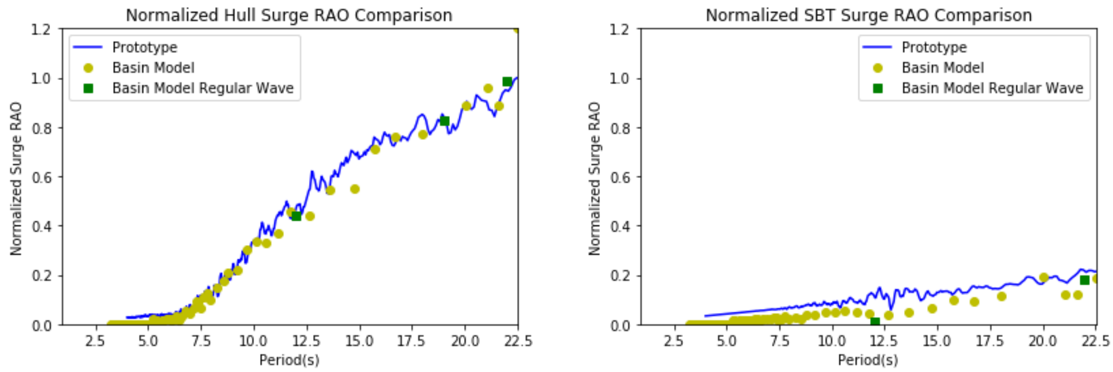


(a) 45 deg (b) 67.5 deg (c) 90 deg

Fig. 1 Normalized Static Offset Curves Comparison

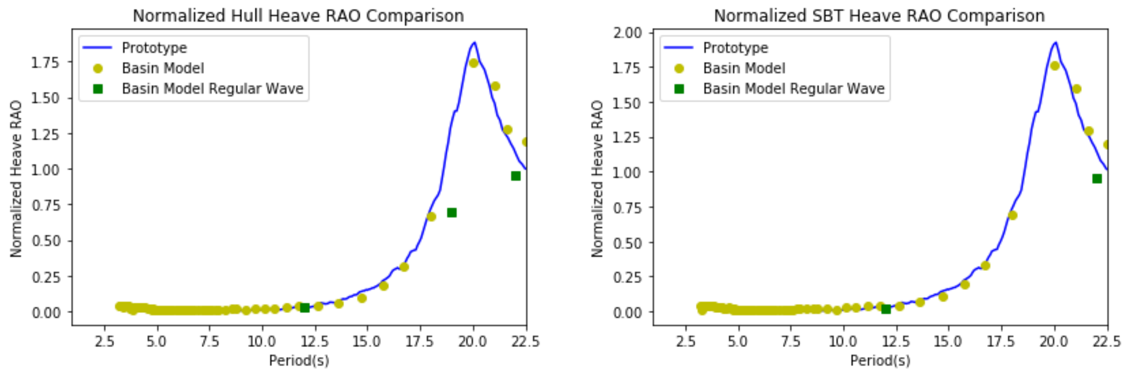
Table 3 LM-FPSO 6-DOF Motion Natural Periods

	Natural Period (s)		
Decay Test	**Basin Model**	**MOM**	**Prototype**
Surge	142.2	133.6	105.3
Sway	114.6	113.4	89.2
Heave	19.8	19.4	19.8
Roll	40.4	43.8	42.3
Pitch	42.9	44.8	43.4
Yaw	87.3	77.8	64.1



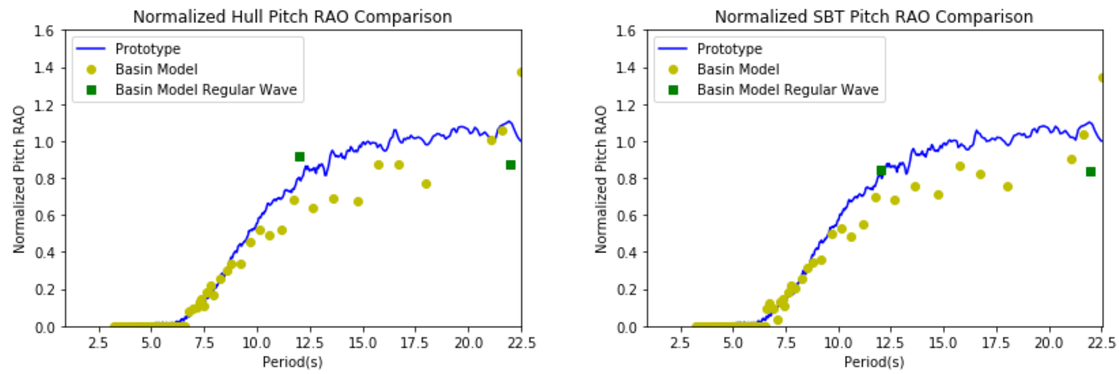
(a) Hull Surge RAO (b) SBT Surge RAO

Fig. 2 Normalized Surge RAO Comparison (45 deg)



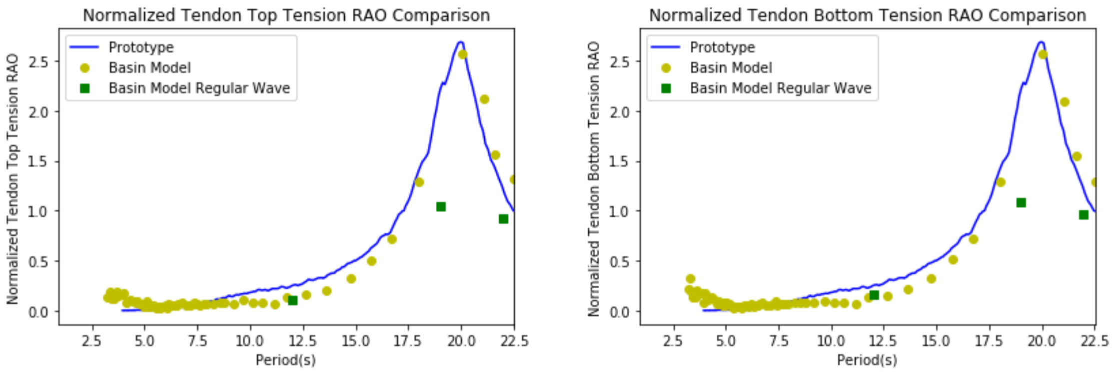
(a) Hull Heave RAO (b) SBT Heave RAO

Fig. 3 Normalized Heave RAO Comparison (45 deg)



(a) Hull Pitch RAO (b) SBT Pitch RAO

Fig. 4 Normalized Pitch RAO Comparison (45 deg)



(a) Tendon Top Tension RAO (b) Tendon Bottom Tension RAO

Fig. 5 Normalized Tendon Tension RAO Comparison (45 deg)

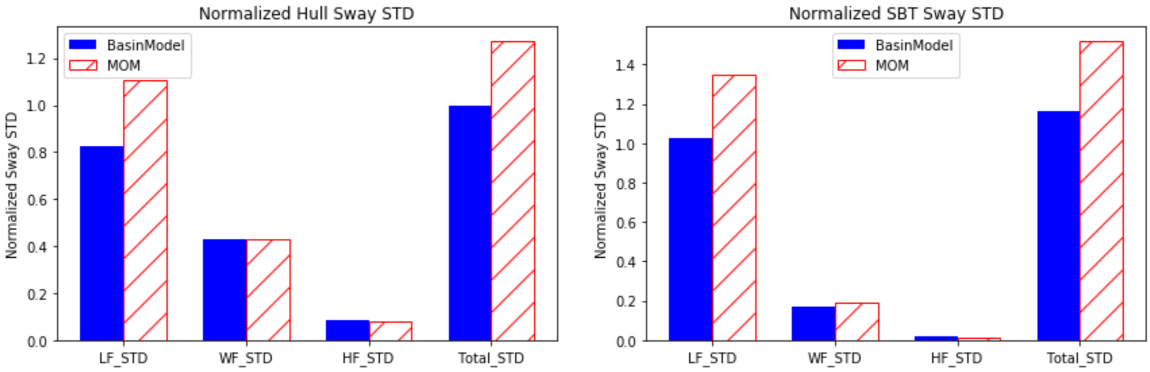
The white noise and regular wave tests have been performed for three wave headings: 45deg, 67.5deg and 90deg. Part of the 45deg white noise test results are shown in Figs. 3-6 White noise and regular wave test comparison shows excellent agreement for both hull and SBT motion RAOs as well as tendon tension RAOs between the basin model measurements and the prototype model predictions.

3.4 Irregular wave tests

In the model test, several irregular sea states, including the 100yr and 10,000yr environment conditions, are performed to investigate the behaviors of the LM-FPSO. The results of hull and SBT 6-DOF motion and tendon top and bottom tensions from basin model and MOM are compared. The dynamic responses are filtered into three parts: low frequency response (LF, >30s); wave frequency response (WF, 5s~30s); high frequency response (HF, <5s). The responses from basin model and MOM are compared for each frequency range. The responses from both of the hull and SBT are normalized by the same factor. Some of the normalized results are compared for 100yr sea states in 45deg heading test in Figs. 7-14. It is noticed that:

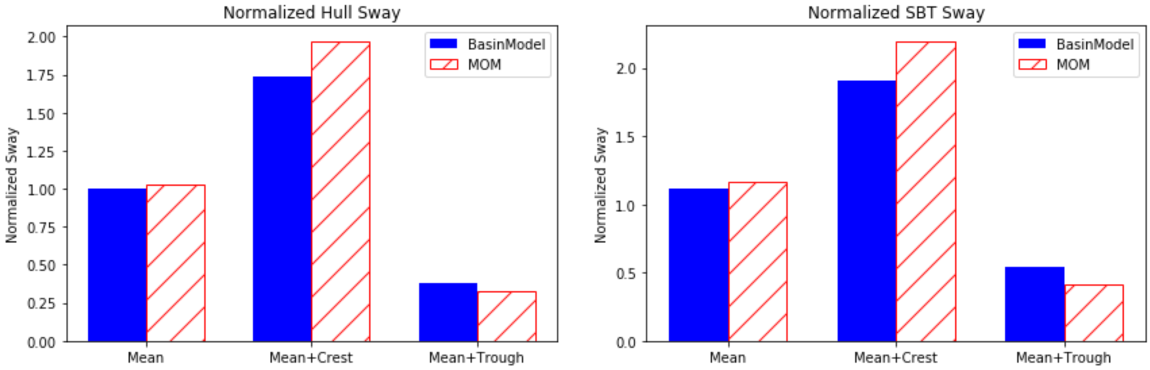
- For all responses the mean from basin model match the mean from MOM. That indicates the correct system set up.
- For horizontal motion of hull and SBT, (such as sway), the WF responses and HF responses from basin model and MOM match very well. There are some differences in the LF responses. This is due to the uncertainty of system damping in the horizontal plane. Calibration factors are derived and applied to prototype model. It is also noticed that the SBT's WF and HF responses are much smaller than the hull, but the LF response is larger.
- For heave and roll motions of hull and SBT, the hull and SBT's responses are almost identical. This indicates the hull and SBT are fully coupled in these modes of motions. The heave and roll responses from basin model match MOM very well.
- For tendon tension responses, the WF responses and LF responses from basin model and MOM match very well. There are some differences in the HF responses. This is due to the tendon's high order effects. The differences are common to be observed in the

model tests for traditional Tension Leg Platform (TLP). Calibration factors are derived and applied to the prototype model.



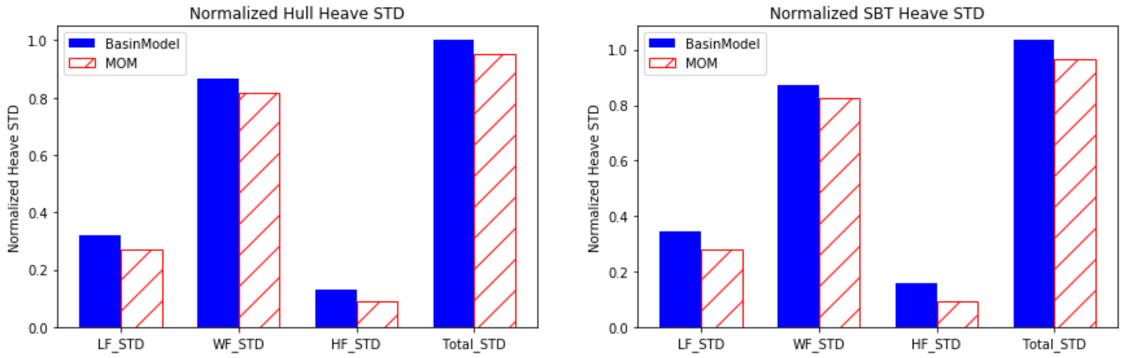
(a) Hull Sway STD (b) SBT Sway STD

Fig. 6 Normalized Sway STD Comparison (100yr, 45 deg)



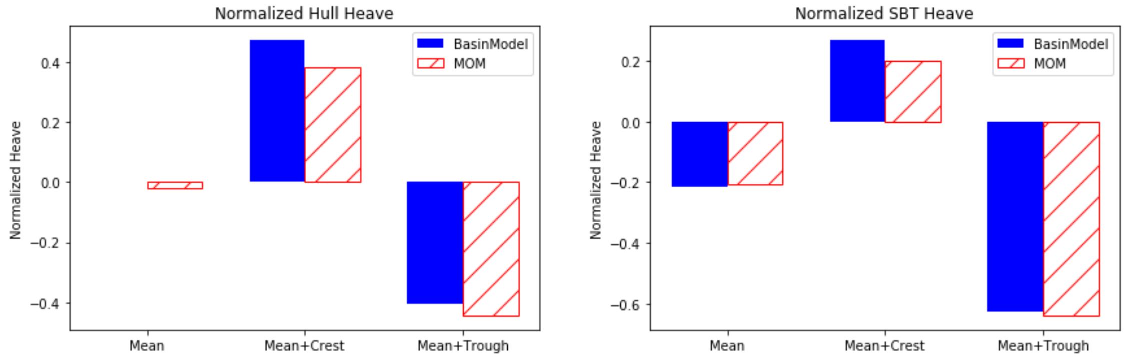
(a) Hull Sway (b) SBT Sway

Fig. 7 Normalized Sway Comparison (100yr, 45 deg)



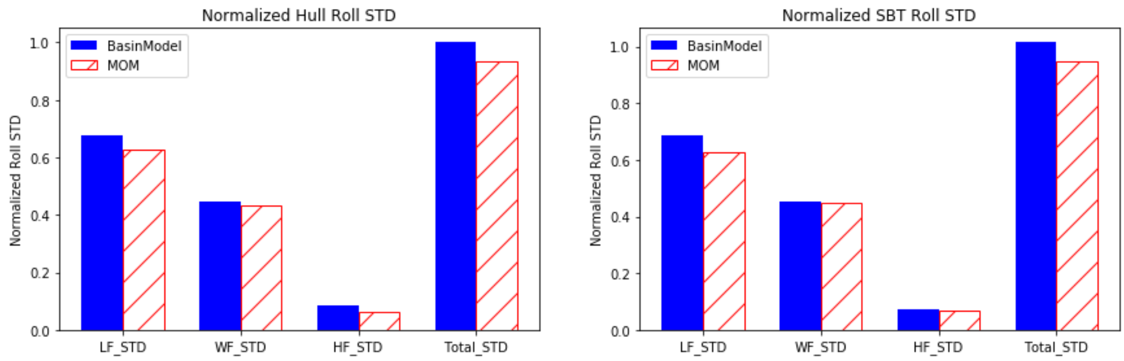
(a) Hull Heave STD (b) SBT Heave STD

Fig. 8 Normalized Heave STD Comparison (100yr, 45 deg)



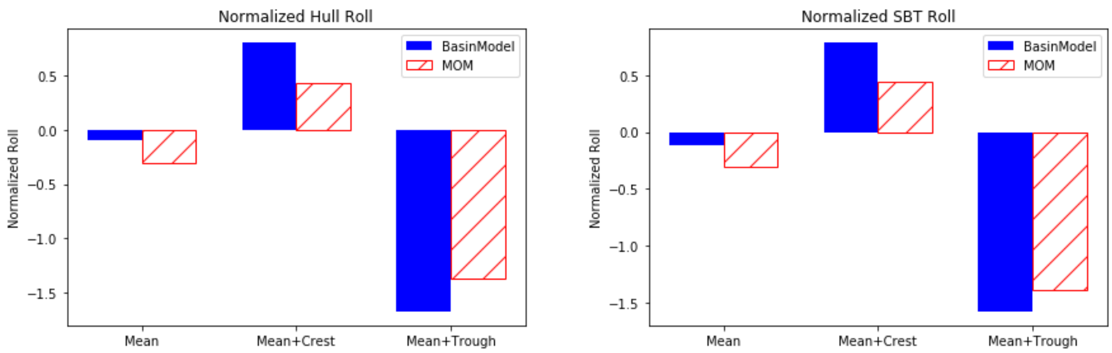
(a) Hull Heave (b) SBT Heave

Fig. 9 Normalized Heave Comparison (100yr, 45 deg)



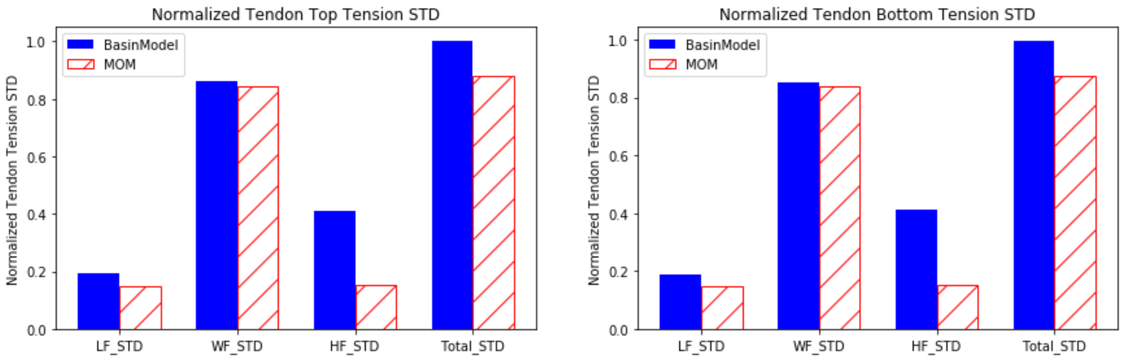
(a) Hull Roll STD (b) SBT Roll STD

Fig. 10 Normalized Roll STD Comparison (100yr, 45 deg)



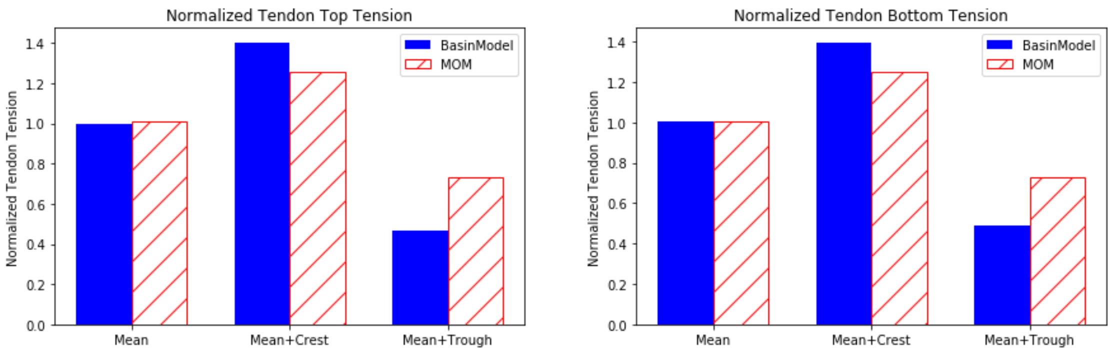
(a) Hull Roll (b) SBT Roll

Fig. 11 Normalized Roll Comparison (100yr, 45 deg)



(a) Tendon Top Tension STD (b) Tendon Bottom Tension STD

Fig. 12 Normalized Tendon Tension STD Comparison (100yr, 45 deg)



(a) Tendon Top Tension (b) Tendon Bottom Tension

Fig. 13 Normalized Tendon Tension Comparison (100yr, 45 deg)

4. Calibrated responses from LM-FPSO prototype model

From the comparisons presented in the previous section, calibration factors are derived for each response and each frequency range. Those factors are applied to the prototype model to calculate the calibrated design responses. Some of the critical calibrated responses for this LM-FPSO design are listed in Table 4. It is noticed that the motion responses from the LM-FPSO are very small verifying the superior motion response offered by the LM-FPSO compared to other types of floaters.

Table 4 LM-FPSO Calibrated Responses

Variable	**Unit**	**10,000yr**	**100yr**
Max Offset	(Water Depth)	12.7%	6.2%
Max Heave (Single Amplitude)	(m)	1.0	0.2
Max Combined Roll/Pitch (Single Amplitude)	(deg)	4.1	1.9
Max Yaw	(deg)	2.3	1.5

5. Conclusions

LM-FPSO is a novel design that provides superior motion responses while preserving the benefits of the conventional FPSO. Wave basin test have been performed to investigate the LM-FPSO performance at the KRISO facility in Korea. A numerical model is created in Orcaflex to represent the basin model properties. Static offset tests, decay tests and white noise and regular wave tests are performed to examine the system setup in the basin and verify that the basin model and numerical models are equivalent in terms of stiffness, damping, mass and added mass. Motions of the hull and SBT as well as the tendon tensions are measured and compared to the corresponding values predicted by the fully coupled time domain analysis in Orcaflex. Excellent agreement has generally been observed which further verify the superior motion response of the LM-FPSO. The calibrated prototype responses are shown to be as small as those motions offered by the Tension Leg Platforms (TLPs) and Spar floaters. Therefore, LM-FPSO is a suitable host to support SCRs and drilling and completion operations in addition to preserving the other advantages of the conventional FPSOs.

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