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Hull Performance Assessment and Comparison of Ship-Shaped and Cylindrical FPSOs With Regards To: Stability, Sea-Keeping, Mooring and Riser Loads In Shallow Water

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ABSTRACT

Floating, Production, Storage and Offloading “FPSO” have become a popular choice since 1980s for marginal and fast-track developments where subsea pipeline is not an economic or feasible solution for export. Field development usually starts with a concept selection procedure which is constituted from a sequence of multi-disciplinary decision making tasks. As limited data is available in the early phase of the development, operators require a robust and rational decision making process to reduce the drawback of immature information. The Multi-Criteria Decision Making (MCDM) process which is used in this paper is an industrial approved and accepted decision making process that can resolve this requirement. This method is commonly used as a decision making method for multiple attributes problems.

The main objective of this study is to illustrate the application of this method for concept selection for shallow water fields. Here the problem is reduced to a selection among two common FPSO concepts: ship-shaped and cylindrical by assessing their performances for the same location. The primary attributes which have been used for performance assessment includes: stability, motions and accelerations, riser stresses and mooring line tensions under both intact and damaged conditions. To simplify the problem, the same topside weight and tank capacity are considered and response comparison is limited to the linear responses induced by wave under full loaded conditions. For both FPSOs spread mooring system with steep-s flexible riser system are considered.

For the given environmental conditions, cylindrical FPSO shows better motion characteristics which lead to smaller mooring and riser loads. This method should be generalized for other shallow water production system by including all the attributes used in the shallow water field development concept selection.

1. Introduction

FPSOs were initially made from converted oil tankers and later were purposely-built vessels to adapt to the local environmental condition operational requirements. FPSO hull design is usually a challenging task compare to other deep water field development concepts due to higher operational demanding requirements, e.g. simultaneous production and offloading. In 1976, Arco initiated the first offshore application of FSU (Floating Storage Units) for Arjun field in the Java Sea offshore Indonesia [1]. It was a concrete barge with steel tanks and it was used to store refrigerated liquefied gas. The first ship-shaped FPSO facility was used for the Castellon field offshore Spain in 1976. Operation started in 1977 with a 10-year field life [2]. Initial FPSOs were dominantly produced from over aged oil tankers and known as converted FPSO. For this type of FPSOs, the prescriptive based shipbuilding standards were applied for hull design, while later experience shows this cannot answer all the design requirements as FPSO is more similar to a floating production platform [3]. Therefore, offshore design rules and standards have been developed and modified based on unique operational requirements of FPSOs. Today tailor made offshore standards are used for FPSO which apply risk-based design approach.

Sanha Liquefied Petroleum Gas "LPG" FPSO creates a new era in the FPSO industry and represents the first time a new-built LPG processing plant is installed on a floating structure [4]. In recent years, the use of natural gas, as an oil alternative energy, has been increased. The construction of floating Liquefied Natural Gas "LNG" (FLNG) is now under investigation around the world to develop marginal gas fields [5].

As FPSO is a floating structure, its stability, seakeeping and hull interaction with mooring and riser systems are primary performance parameters. Stability should be assessed prior to motion, mooring and riser loads. The stability design criteria apply for both intact and damage conditions. Providing a hull with accepted stability characteristics, a hydrodynamic model can be developed to be used for motion, mooring and riser analysis.

The stability design parameters may directly or indirectly contribute to the motions, as well as mooring and riser loads, e.g. vertical motion of FPSO which is important for green water and riser loads study are directly affected by water plane area [6]. The geometry of the hull plays a primary role in the stability characteristics. The hull geometry is usually represented by a set of basic parameters such as: block coefficient (C_b), amidships section coefficient, longitudinal prismatic coefficient and water plane area coefficient (C_{wp}). With these parameters one can compare the stability performance of two concepts. For example, higher block coefficient is more desired for FPSOs as it increases the crude oil capacity. These parameters mutually affect each other and a designer should consider these effects to reduce their design effort [7].

As mentioned earlier, stability parameters may affect the dynamic characteristics of the hull, but this is not always a straight forward effect. For example, decreasing and increasing C_{wp} in the fore region of hull, can directly reduce deck wetness and increase probability of slamming respectively, but effect of C_{wp} on roll motion is related to the natural period of the hull as well as wave dominating frequency and cannot be studied independently [8].

Seakeeping ability is a measure of how an FPSO behaves under different dynamic loading conditions and environmental effects. Seakeeping characteristics is directly defining the uptime availability of FPSO for continuous production at the field and non-stop offloading to the shuttle tanker.

The seakeeping performance assessment is performed based on the probability of exceeding specified amplitude of FPSO motions for safe operations. Mathematically the response characteristics of the hull is represented by a single function, RAO (Response Amplitude Operators) which can be calculated from diffraction-radiation software or frequency assessment of model test time series. The extreme motions which are used as characteristic responses for seakeeping assessment are calculated by application of extreme environmental conditions of the given field on the RAO of each degree of freedom "DOF". The predicted motions are compared to the motion limit states to obtain the operability indices [9]. Seakeeping performance of the hull can be characterized by crew comfort and safety, operational uptime of production systems, operational effectiveness of offloading to shuttle tanker and helicopter maneuvering demands [10]. Several primary parameters determine the seakeeping characteristics including: hull size and dimensions, hull form and freeboard as well as weight distribution. A larger FPSO usually has better motion than a smaller FPSO, because increasing the size and weight of the hull increases the natural periods of the motions close to the dominating wave period. Consistently, a heavier FPSO usually has smaller motions comparing to a lighter one due to larger inertia of the hull [11].

To study the wave motion response of FPSOs, the approved radiation-diffraction potential method is frequently used. The radiation-diffraction potential theory calculates inviscid hydrodynamic characteristics of the hull and wave exciting forces on the floating body using three velocity potentials known as: incident, radiation and diffraction in the frequency domain. This method is only applicable for large volume bodies such as FPSO [12]. Pitch and heave motions, slamming, green water ingress on the deck are numbered as seakeeping challenges for FPSOs which can be studied with this method [13].

Selection of proper mooring and riser system for FPSO can be a challenging task for specific environmental conditions as they are both a cost driver for the project on one hand and safety critical components on the other hand. That means increasing the safety of the system may exceed the cost margin of the project. Long-term safe operation of an FPSO is always an important operational demand and mooring system is a component which is used to alleviate this demand. As mentioned the mooring system is a safety critical component of an FPSO and its design depends on a number of factors including size of FPSO, water depth, environmental conditions, number of risers, etc [14]. For proper design of the mooring system, the applied numerical model should be able to consider six degrees of freedom wave frequency motions (in surge, sway, heave, roll, pitch and yaw); horizontal excursion due to low frequency drift force (in surge,

sway and yaw) and the effect of non-collinear environments. The design parameters for the mooring system includes: design pre-tension, fairlead and anchor point coordinates, mooring pattern, line configuration and characteristics of components [15].
Mooring system should be designed for both intact and damaged conditions. In mooring system design as failure of one mooring line can lead to a loss of property and major environmental damage, this condition should be considered as one of accidental load cases. Effects of line failure are considered in both steady and transient conditions [16].
Riser systems are one of the important key elements for deep water offshore oil and gas field development. As riser system is one of the safety critical components, engineers should always try to improve the riser solution for FPSOs. Riser systems sometime constitute a considerable portion of the development costs of floating production systems when the field characteristics and development plan requires a quite high number of risers in deep waters.
The main purpose of this paper is to establish a systematic approach for performance assessment of ship-shaped and cylindrical FPSOs under full loaded condition as design driving loading condition which is concluded in previous study by the authors [17]. The proposed FPSOs with spread mooring system and Steep-s riser configuration in water depth of 100 meters are selected as nominated case studies. Processing facilities, flare tower and other major equipment on the deck are modeled as a set of point mass. As the super structure geometry and related projection area and drag coefficient are not available for this study, directional wind force is not considered. Therefore, only wave and current forces will be used as environmental actions. Therefore, the scope of this study is limited to linear motions and first order forces induced by wave and current.

2. FPSO performance assessment process

The concept selection procedure for shallow water field development is modeled as a Multi-Criteria Decision Making (MCDM) problem [18]. Several types of MCDM methods identified through reviews [19] including: Multi-attribute utility theory, Analytic Hierarchy Process (AHP), case-based reasoning, data envelopment analysis, simple multi-attribute rating technique, and goal programming. Analytical Hierarchy Process (AHP) is often used as a decision making method for concepts where multiple attributes decision parameters must be considered and compared.
Analytical Hierarchy Process (AHP) is a tool developed by Saaty (1996) for solving multi-attribute decision making problems. The first step in building an AHP hierarchy is to identify critical attributes affecting the decision or system behavior. These attributes are then organized into a hierarchy structure that follows a logical breakdown or categorization. Next, the relative influence of each attribute on system performance is evaluated by engineering tools and calculations or by expertise judgments.
To quantify the overall efficiency of the system, considering the contribution of all attributes, an OMOE (Overall Measurement of Efficiency) function is defined which represents the contribution of all important attributes. Due to the dependency between attributes, the objective function OMOE, consists of two levels of attributes, i.e. the higher level, MOE (Measurement Of Efficiency) and the lower level, MOP (Measurement Of Performance). Usually dividing the attributes to two levels of attributes and sub attributes is sufficient which depends on detailed level of numerical analysis and available information. MOPs are the lowest level parameters which should be quantified and measured for each concept.
As each attribute has a different importance in the design, their contribution in the MOE and OMOE should be similar to their importance in the design. Therefore, the relative importance of each MOP and MOE are weighted by pair-wise comparison of the parameters based on their contribution in total response. The weight values are usually determined through a parameter sensitivity analysis by numerical model or through a brain storming workshop with expertise in each discipline by providing a questionnaire to the expertise to determine the relative importance of each variable. The primary weight factors S_i collected from expertise or parameter study will be normalized for each related set of MOP and MOE consequently as shown by Eq.(3-5). The normalized weights will be used to calculate MOE and OMOE.
The formula given in Eq.(1) and Eq.(2) are used to calculate the OMOE for each concept at the end. In these equations *n* and *m* represents the number of selected variables and W_i and W_j represents the weight factors selected for each MOP and MOE respectively.
The accuracy of this method primarily depends on the number of MOP and MOE parameters and how accurate the value of each MOPs is calculated [20].

$$S = \sum_{i=1}^{n} S_i \tag{1}$$

$$W_i = \frac{S_i}{S} \tag{2}$$

$$W_1 + W_2 + \ldots + W_n = 1 \tag{3}$$

$$MOE_i = \sum_{j=1}^{m} W_j \times MOP_j \tag{4}$$

$$OMOE = \sum_{i=1}^{n} W_i \times MOE_i \tag{5}$$

An example of pairwise comparison for "n" variables "X_i" is presented in weighting matrix of Table 1 by weighting factors "Sw_{ij}". In the next step each column is normalized by Eq.(1), Eq.(2) and Eq.(3) [20].

Table 1. Weighting matrix

	X_1	X_2	X_3	X_4	X_5	.	X_n
X_1	1	Sw_{21}	Sw_{31}	Sw_{41}	Sw_{51}	$Sw_{.1}$	Sw_{n1}
X_2	Sw_{12}	1	Sw_{32}	Sw_{42}	Sw_{52}	$Sw_{.2}$	Sw_{n2}
X_3	Sw_{13}	Sw_{23}	1	Sw_{43}	Sw_{53}	$Sw_{.3}$	Sw_{n3}
X_4	Sw_{14}	Sw_{24}	Sw_{34}	1	Sw_{54}	$Sw_{.4}$	Sw_{n4}
X_5	Sw_{15}	Sw_{25}	Sw_{35}	Sw_{45}	1	$Sw_{.5}$	Sw_{n5}
.	$Sw_{1.}$	$Sw_{2.}$	$Sw_{3.}$	$Sw_{4.}$	$Sw_{5.}$	1	$Sw_{n.}$
X_n	Sw_{1n}	Sw_{2n}	Sw_{3n}	Sw_{4n}	Sw_{5n}	Sw_{6n}	1
	S_1	S_2	S_3	S_4	S_5		S_n

The stability characteristic, seakeeping performance as well as mooring and riser loads are selected as the primary MOE. Stability characteristics of an FPSO consists of intact and damage conditions. These two conditions are selected as nominated MOEs of the stability as indicated in Table 2. Range of stability and GZ-φ diagram are the MOPs for stability; where φ is the heel angle and GZ is the righting lever. MOPs of the intact and damage stability are the same but calculated under different conditions. IMO [21] and MARPOL [22] stability criteria are used for intact and damage stability checks respectively. According to DNV standard [23] these intact and damage criteria are applicable for ship- shaped and cylindrical FPSOs. For damage stability assessment, three tanks assumed to be fully flooded, which are: ballast tank 2port, ballast tank 3port and ballast tank 4port [23] as shown in Figure 4 .

Table 2. Stability MOEs and MOPs [21,22]

MOE_{11}: Intact stability; IMO criteria
MOP_{111}:Area under the righting lever curve between the angles of heel of 0° and 30° shall not be less than 3.1513 m.deg.
MOP_{112}:Area under the righting lever curve between the angles of heel of 0° and 40° shall not be less than 5.1566 m.deg.
MOP_{113}:Area under the righting lever curve between the angles of heel of 30° and 40° shall not be less than 1.7189 m.deg.
MOP_{114}:Angle of maximum GZ shall not be less than 25.0 deg.
MOP_{115}:Initial GMt shall not be less than 0.150 m.
MOP_{116}:Range of positive stability shall not be less than 10.0 deg.
MOE12: Damage stability; MARPOL criteria
MOP_{121}:Range of positive stability shall not be less than 20.0 deg.
MOP_{122}:Residual righting lever shall not be less than 0.100 m.
MOP_{123}:Area under GZ curve shall not be less than 1.0027 m.deg.

FPSO response characteristics is characterized by Response Amplitude Operator (RAO) calculated by frequency domain-based method. By considering the motions of FPSO in time domain as a narrow-banded Gaussian process, the significant motion and extreme values responses (Rayleigh distribution) can be calculated from the relevant response spectrum as shown in Eq.(6-8) [16].

$$\sigma_{significant} = \pm 2 \times s \tag{6}$$

$$E_{\max} = +s \times \sqrt{(2Log_e(\frac{t}{t_z}))} \tag{7}$$

$$E_{\min} = -s \times \sqrt{(2Log_e(\frac{t}{t_z}))} \tag{8}$$

Where; $\sigma_{significant}$ is the significant value of the response, s is the response standard deviation, E_{max} is the most probable maximum value, E_{min} is the most probable minimum value of the response, t is the duration of the response time series to be statistically stationary (3hr) and t_z is the average zero up-crossing period of the response. For the low-frequency motions, t_z can be taken as the natural period for the appropriate degree-of-freedom of the combined structure/riser/mooring system t_n, which can be estimated by Eq.(9) [16].

$$t_n = 2 \times \pi \times \sqrt{\frac{M}{K}} \tag{9}$$

In this equation, M is the system mass including added mass (kg) and K (N/m) is the system stiffness for the appropriate degree-of-freedom at the structure's mean position. The motion at the center of gravity is used as a reference to calculate the characteristic responses in Eq.(6-8).

According to API [24] the maximum limit of FPSO offset should be in 25-30 percentage of water depth in intact condition and 30-50 percentage of water depth in one mooring line broken condition.

The personnel comfort and proper operation of machinery and process systems onboard are influenced by FPSO motions and accelerations. The primary important factor that affects FPSO motions is obviously the FPSO size, particularly the length. The performance of the process system in the topside and personnel comfort are limited by acceleration of the hull. Therefore, significant acceleration amplitudes in six degrees of freedom need to be calculated as a part of seakeeping performance assessment. Calculation of significant acceleration amplitudes are similar to significant response amplitudes mentioned in Eq.(6). The personnel comfort is characterized by MSDV (Motion Sickness Dose Value) based on ISO 8041[25] and ISO 2631-1[26]. The vertical Motion Sickness Dose Value (MSDVZ), which is calculated using vertical acceleration in $m/s^{1.5}$, is defined by Eq.(10).

$$MSDV_z = \sqrt{\int_0^t a^2{}_{zw}(t)dt} \tag{10}$$

Here, a_{zw} (t) is vertical acceleration (m/s^2) as defined by Eq.(11) and W_f is a weight factor to limit the applied frequency range (0.1 – 0.5 Hz) that calibrated based on general human comfort zone and t is the duration of the time series or period of time which personnel are subjected to the motion.

$$a_{zw} = \sqrt{(\sum_i (\mathrm{W_f} \times \mathrm{a_i})^2)} \tag{11}$$

Table 3 [25] shows the applied criteria for the MSDV calculation.

Table 3. Comfort criteria [25]

Frequency range	Acceleration measurement	Max level
0.1-0.5 Hz	$MSDV_z$	30 $m/s^{1.5}$

The FPSO response in each degree of freedom are simply calculated by applying the wave spectrum on the associated RAO which provide response spectra for the given wave and degree of freedom. The root mean square of the area under the response spectra gives the standard deviation of the response. The area under the RAO curve represents the amount of energy the FPSO will absorb from encountered wave [27]. The selected seakeeping MOEs and related MOPs are listed in Table 4 [28].

Table 4. Seakeeping MOEs and MOPs [28]

MOE_{21}:Significant response amplitude	MOE_{22}:Significant acceleration amplitude	MOE_{23}:Area under curve of RAO amplitude
MOP_{211}:Surge	MOP_{221}:Surge	MOP_{231}:Surge
MOP_{212}:Sway	MOP_{222}:Sway	MOP_{232}:Sway
MOP_{213}:Heave	MOP_{223}:Heave	MOP_{233}:Heave
MOP_{214}:Roll	MOP_{224}:Roll	MOP_{234}:Roll
MOP_{215}:Pitch	MOP_{225}:Pitch	MOP_{235}:Pitch
MOP_{216}:Yaw	MOP_{226}:Yaw	MOP_{236}:Yaw
	MOP_{227}:MSDV	

Considering the linear response assumption, the principle of superposition can be used which allows calculation of response in frequency domain for WF and LF parts separately [28].
This principle is used to calculate the mooring and riser tension loads. Therefore, the maximum offset is calculated as a superposition of maximum displacement due to mean offset, wave frequency and low frequency FPSO motion as shown in Figure 1 [29].

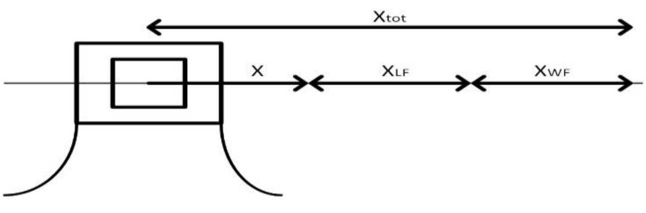

Figure 1. FPSO offset schematic [29]

According to API-RP-2SK, the maximum offset is the larger of either Eq.(12) or Eq.(13) [30].

$$X_{\max} = X_{mean} + X_{LF\max} + X_{WFsig} \tag{12}$$

$$X_{\max} = X_{mean} + X_{WF\max} + X_{LFsig} \tag{13}$$

Where; X_{mean} is the mean offset induced by static forces, X_{max} is the total maximum offset, X_{WFmax} is the maximum wave frequency motion, X_{WFsig} is the significant wave frequency motion, X_{LFmax} is the maximum low frequency motion and X_{LFsig} is the significant low frequency motion. The quasi-static analysis is applied to calculate the maximum mooring line tension in which the tension at the top end (fairlead) of the mooring line dependents only on the top end distance from the anchor point as in Eq.(14) [30].

$$T = T(r) \tag{14}$$

Where, r = (x, z) is the instantaneous distance between the anchor point and the associated mooring fairlead position on the hull. According to the mooring standard, quasi-static tension for the fairleads $T_{quasi-static}$, is calculated as a function of max displacement X_{max} and mean offset X_{mean}. Then the total mooring line tension can be calculated using Eq.(15) [30].

$$T_{dynamic} = T_{quasi-static}(X_{\max}) - T_{mean}(X_{mean}) \tag{15}$$

Given the offset of the hull as a superposition of characteristic WF and LF motions the dynamic mooring line loads can be calculated by Eq.(16) [30].

$$\begin{aligned} T_{dynamic} &= T_{quasi-static}[X_{\max} - X_{WF\max}] \\ &- T_{mean}(X_{mean}) + T_{WF\max} \end{aligned} \tag{16}$$

In which, $T_{quasi-static}$ [X_{max} - X_{WFmax}] is the quasi-static tension calculated at (X_{max} - X_{WFmax}) position and T_{WFmax} is defined by Eq.(17) [30].

$$T_{WF\max} = \sigma_{T-WF}[X_{\max} - X_{WF\max}]\sqrt{2\ln N_{WF}} \tag{17}$$

In Eq.(17), σ is standard deviation and N_{WF} is the number of low-frequency oscillations during three hours stationary period.
The permissible mooring line tension is determined by fraction pf MBS[1] of mooring line cable [31]. MBS represents the minimum breaking strength of the line. Chain type mooring system with the MBS of 690 N/mm^2 [31] is considered for this study. Table 5 shows standard criteria [31] for maximum mooring line tension in intact and damage (one line broken) condition which are used to calculate the related MOP and MOE.

[1] Minimum Breaking Strength

The riser axial and Von-Mises stresses are calculated at its mid-point and two ends to be used as related MOP. The riser is constructed from the X60 steel with SMYS (Specified Minimum Yield Strength) equal to 415 MPa. Table.5 shows standard criteria [32, 33] for maximum allowable riser axial and Von-Mises stress under intact and damage (one line broken) conditions. Maximum riser stress occurs at TDP (Touch Down Point) of the riser.

Table 5. Mooring line tension and riser stress MOPs [32,33]

MOE_{31}:Intact condition	
MOP_{311}: Mooring line tension	50% MBS
MOP_{312}: Axial stress in TDP	60% SMYS
MOP_{313}: von-Mises stress in TDP	60% SMYS
MOE_{32}:One mooring line broken (damage) condition	
MOP_{321}: Mooring line tension	80% MBS
MOP_{322}: Axial stress in TDP	90% SMYS
MOP_{323}: von-Mises stress in TDP	90% SMYS

A set of approved engineering tools are used to calculate the required MOPs for both concepts. The stability properties are calculated with MAXSURF. The hydrodynamic properties followed by seakeeping performances as well as mooring and riser forces are calculated with ANSYS AQWA hydrodynamic module. For verification purpose the results are benchmarked with another dedicated offshore engineering tool ORCAFLEX which is frequently used for mooring and riser load analysis. Figure 2 shows design procedure of FPSO hull in this study. The flowchart in Figure 3 makes a glance to the whole procedure used in this study.

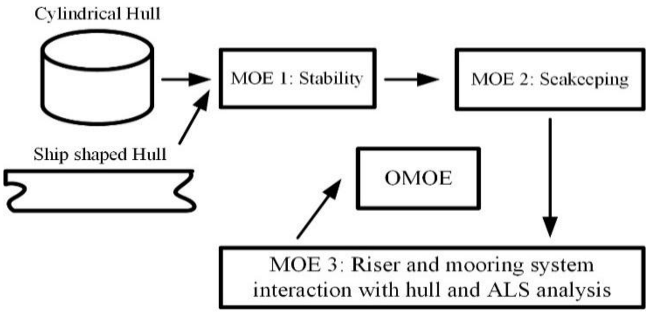

Figure 2. Hull design sequence

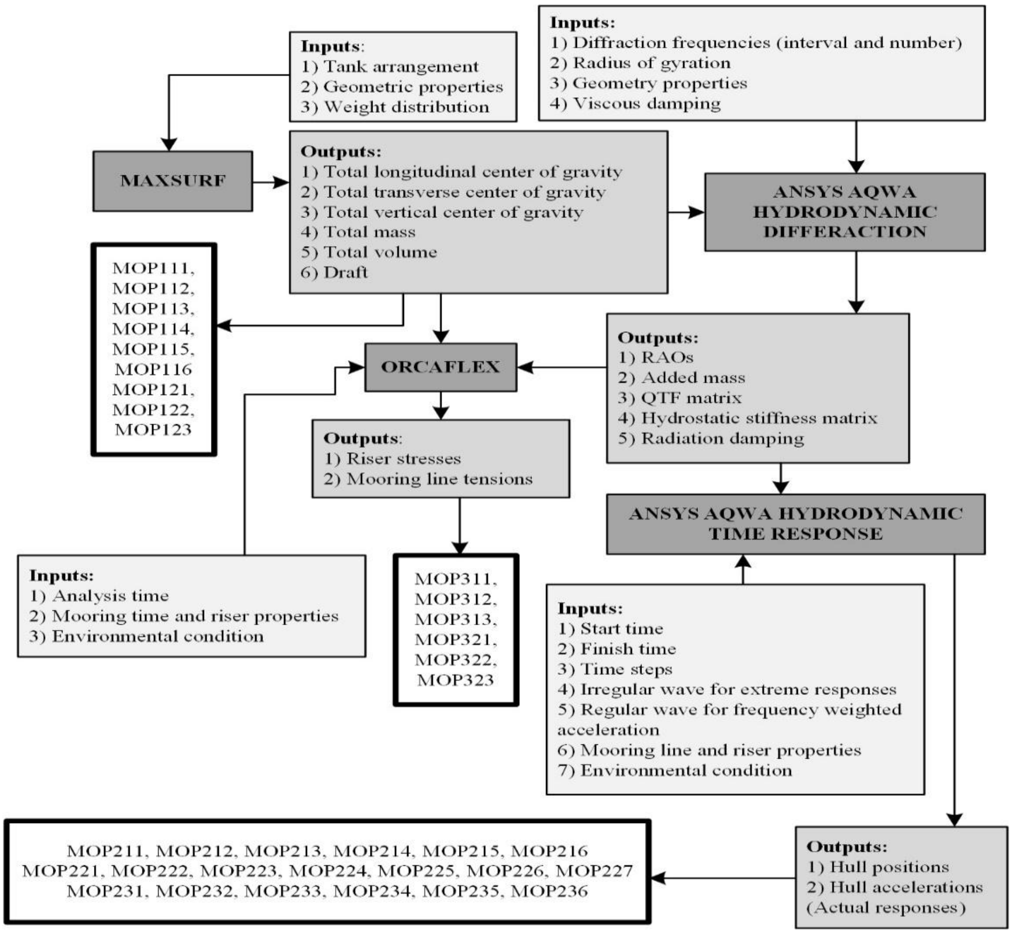

Figure 3. A complete view of evaluation process for providing MOPs of MOEs

3. Case study

This section presents the application of the concept evaluation method for the ship-shaped and cylindrical FPSOs. The fundamental characteristics of the selected cases are listed in Table 6. Figure 4 shows the tank arrangement used for stability calculation. FPSO hull models in MAXSURF are shown in Figure 5. The loading conditions for both cases is listed in Table 7. Figure 6 shows the arrangement and configuration of the FPSOs mooring system. When spread mooring system is used, risers are connected to the sides at mid-ship of the hull by riser porch. The mechanical properties for mooring line chain and steep-s flexible riser are presented in Table 8.

Table 6. FPSOs specification

FPSO hull form	Ship shape	Cylindrical
Length [m]	270	-
Breadth [m]	48	-
Height [m]	30	40
Diameter [m]	-	80
Light weight [tons]	52600	42280
Number of risers	4	4
Number of mooring lines	8	8

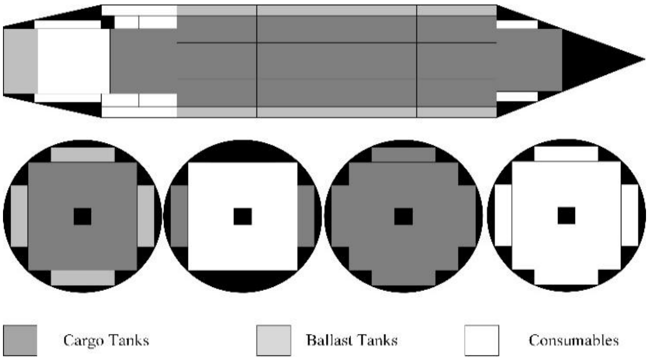

Figure 4. FPSO tank arrangement

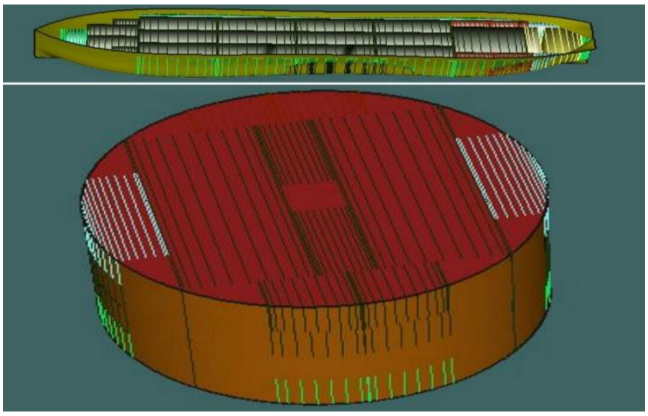

Figure 5. FPSO Hull forms

Table 7. Loading conditions used for FPSOs

Loading condition	Percentage of oil cargo tanks	Percentage of ballast tanks	Percentage of consumables
Full load	80%	5%	50%

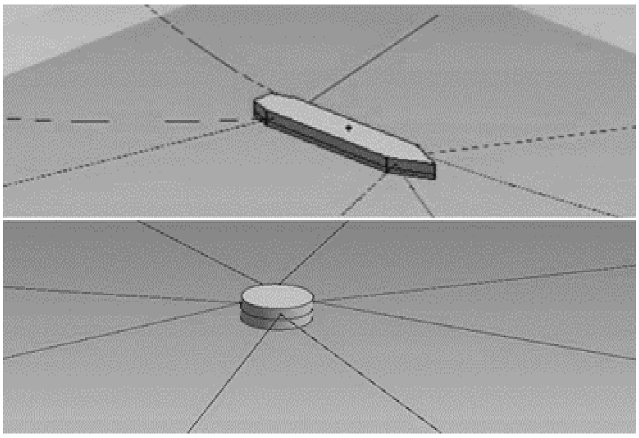

Figure 6. Mooring system configuration

Table 8. Mooring line and riser properties

Item	Mooring line	Riser
Type	Non-linear catenary	Non-linear catenary
Length (m)	1360	200
Mass / unit length (kg/m)	348	150.353
Equivalent CSA (m²)	0.161	0.0185
Stiffness, EA (MN)	1603	3444
Maximum tension (MN)	7.5	7.5
Equivalent diameter (m)	0.454	0.232
Longitudinal drag coefficient	0.025	0.025
Transverse drag coefficient	1	1

The environmental conditions used to calculate the responses are as Table 9. For ship-shaped FPSO with spread mooring system the heading is usually adjusted to the predominant wave direction. According to the numerical model requirements indicated in software manual, the time step should not be larger than 1/40 of shortest wave period. The accurate quadratic damping matrix of the hull and mooring system are usually estimated from CFD[1] or laboratory model test in the later stage of the design mainly for design optimization purpose. In the early design stage which these data are not available a rough estimation as 20% of critical damping can be assumed [31].

Table 9. Environment condition and analysis settings

Water depth (m) / Water density (kg/m³)	100 / 1025
(Hs) (m) / (Tp) (s) / Current speed	5.1 / 9.9 /0.73
Analysis time (s) / Time Step (s)	1200 / 0.05
Analysis type / Wave spectrum type	(Irregular wave - Regular wave) / (JONSWAP-Airy wave theory)
Number of wave frequencies/ Wave frequencies interval (Hz)	30 / 30
Direction of wave (deg) / Current (deg)	180 / 180

The criteria for pair-wise comparison and weighting of the selected MOEs and MOPs are listed in Table 10.

[1] Computational Fluid Dynamics

Table 10. Basis for pairwise comparison of attributes, sub attributes

Attributes importance degree	Weights
Strongly more important	5
Weakly more important	3
Equally important	1
Weakly less important	0.3
Strongly less important	0.2

4. Results and Discussion

The hydrostatic properties which are calculated with MAXSUR are shown in Table 11.

Table 11. Hydrostatic properties of case studies

FPSO hull type	Ship shaped	Cylindrical
Heel angle (deg)	0	0
Trim angle(deg)	0.3002	0.4001
Draft (m)	19.141	19.227
Freeboard (m)	10.859	20.773
I_{xx} (kg.m²)	46.46×10^{9}	91.68×10^{8}
I_{yy} (kg.m²)	79.47×10^{10}	91.69×10^{8}
I_{zz} (kg.m²)	85.96×10^{10}	13.44×10^{10}
Total mass (tons)	17.44×10^{4}	16.80×10^{4}
Center of gravity (x,y,z) (m , m, m)	(1.755,0,-1.243)	(0.229,0,3.526)
(GM_L) (m)	288.106	32.054
(GM_T) (m)	2.869	28.657
Block coefficient (C_b)	0.78	0.95

A comparison of GZ-$\boldsymbol{\varphi}$ diagram for both cases under intact condition is shown in Figure (a) at the appendix. The calculated values for stability MOPs and associated weight factors are listed in Table 12.

Table 13 shows the calculated values and weight factors for seakeeping MOPs. Heave, roll and pitch acceleration amplitudes of ship-shaped and cylindrical FPSO are compared in Figure (b), Figure (c) and Figure (d) at the appendix. The result show that heave, roll and pitch accelerations of cylindrical FPSO is considerably smaller than the ship-shaped.

Table 12. Stability MOP values

Measurement of performance		Weighting coefficients	Ship shape	Cylindrical
MOP_{111}	Value[m.deg]	W_{111}: 0.05	21.9	217.1
	Score		0.1	1
MOP_{112}	Value[m.deg]	W_{112}: 0.05	39.5	327
	Score		0.12	1
MOP_{113}	Value[m.deg]	W_{113}: 0.05	17.6	109.8
	Score		0.16	1
MOP_{114}	Value[deg]	W_{114}: 0.05	44.5	30.9
	Score		1	0.69
MOP_{115}	Value[m]	W_{115}: 0.05	2.0	31.9
	Score		0.06	1
MOP_{116}	Value[deg]	W_{116}: 0.75	69.7	88.1
	Score		0.79	1
MOP_{121}	Value[deg]	W_{121}: 0.75	43.6	61.4
	Score		0.71	1
MOP_{122}	Value[m]	W_{122}: 0.125	0.3	2.3
	Score		0.13	1
MOP_{123}	Value[m.deg]	W_{123}: 0.125	2.7	14.9
	Score		0.18	1

Table 13. Seakeeping MOP values

Measurement of performance		Weighting coefficients	Ship shape	Cylindrical
MOP_{211}	Value [m]	W_{211}: 0.25	1.036	0.773
	Score		0.7	1
MOP_{212}	Value [m]	W_{212}: 0.25	0.002	0.001
	Score		0.5	1
MOP_{213}	Value [m]	W_{213}: 0.24	0.414	0.198
	Score		0.48	1
MOP_{214}	Value [deg]	W_{214}: 0.09	0.0012	0.0011
	Score		0.91	1
MOP_{215}	Value [deg]	W_{215}: 0.09	0.536	0.193
	Score		0.36	1
MOP_{216}	Value [deg]	W_{216}: 0.08	0.0003	0.0001
	Score		0.33	1
MOP_{221}	Value [m/s²]	W_{221}: 0.25	0.106	0.087
	Score		0.82	1
MOP_{222}	Value [m/s²]	W_{222}: 0.25	0.00003	0.00001
	Score		0.33	1
MOP_{223}	Value [m/s²]	W_{223}: 0.12	0.21	0.09
	Score		0.43	1
MOP_{224}	Value [deg/s²]	W_{224}: 0.09	0.0005	0.0001
	Score		0.2	1
MOP_{225}	Value [deg/s²]	W_{225}: 0.09	0.03	0.005
	Score		0.14	1
MOP_{226}	Value [deg/s²]	W_{226}: 0.08	0.0007	0.0003
	Score		0.43	1
MOP_{227}	Value [$m/s^{1.5}$]	W_{227}: 0.12	23.51	16.64
	Score		0.7	1
MOP_{231}	Value [ ]	W_{231}: 0.25	0.067	0.064
	Score		0.96	1
MOP_{232}	Value [ ]	W_{232}: 0.25	0.00008	0.00003
	Score		0.38	1
MOP_{233}	Value [ ]	W_{233}: 0.24	0.77	0.36
	Score		0.47	1
MOP_{234}	Value [ ]	W_{234}: 0.09	0.004	0.001
	Score		0.25	1
MOP_{235}	Value [ ]	W_{235}: 0.09	0.37	0.26
	Score		0.7	1
MOP_{236}	Value [ ]	W_{236}: 0.08	0.00007	0.00001
	Score		0.14	1

MOP values and weight factors for mooring and riser are listed in Table 14.

Table 14. Mooring and riser MOP values with hull

Measurement of performance		Weighting coefficients	Ship shape	Cylindrical
MOP_{311}	Value [N/mm²]	W_{311}: 0.42	303.6	285.8
	Score		0.94	1
MOP_{312}	Value [MPa]	W_{312}: 0.28	94.1	87.3
	Score		0.93	1
MOP_{313}	Value [MPa]	W_{313}: 0.3	87.3	82.5
	Score		0.95	1
MOP_{321}	Value [N/mm²]	W_{321}: 0.42	412.5	392.4
	Score		0.95	1
MOP_{322}	Value [MPa]	W_{322}: 0.28	97.2	91.3
	Score		0.94	1
MOP_{323}	Value [MPa]	W_{323}: 0.3	92.6	87.1
	Score		0.94	1

Table 15 shows the weight coefficients considered for the MOEs of this study.

Table15. MOEs weighting coefficients

Stability	Weighting coefficient
MOE_{11}	W_{11}: 0.75
MOE_{12}	W_{12}: 0.25
Seakeeping	**Weighting coefficient**
MOE_{21}	W_{21}: 0.63
MOE_{22}	W_{22}: 0.11
MOE_{23}	W_{23}: 0.26
Mooring and riser interaction with hull	**Weighting coefficient**
MOE_{23}	W_{31}: 0.62
MOE_{23}	W_{32}: 0.38

The results of this work should be considered in the framework of the assumptions made in this study. More accurate comparison can be achieved when the numerical model is matured with the results form an ocean basin model test and wind tunnel test. Therefore, the OMOE is not calculated for this study and comparison is limited to the MOEs given in Table 2, Table 4 and Table 5. The MOEs are calculated according to Eq.(4) and related weight factors and MOPs are used according to Table 12, Table 13, Table 14 and Table 15. Final results of MOEs for two cases are listed in Table 16.

The simulation length and time step selected in this analysis is based on the Low Frequency Perturbation (LFP) method. The length of the simulated time series should be at least three hours to provide stationary stochastic properties and allows the application of Rayleigh distribution for extreme response. The stochastic evaluation of the time series, as shown in Figure (e) in appendix, illustrates that the response is stationary even after 1200 second. The surge and sway significant response amplitudes of the ship-shaped and surge significant response amplitude of cylindrical FPSOs are shown in Figure (e) of the appendix.

Table 16. Final values of MOE for two cases

Description	Ship shape FPSO	Cylindrical FPSO
MOE_{11}:Intact stability	0.66	0.97
MOE_{12}:Damage stability	0.56	1
MOE_{21}:Significant response amplitude	0.55	1
MOE_{22}: Significant acceleration amplitude	0.48	1
MOE_{23}:Area under curve of RAO amplitude	0.7	1
MOE_{31}:Mooring and riser interaction with hull (intact)	0.93	1
MOE_{32}: Mooring and riser interaction with hull (damage)	0.93	1
MOE_{1}: Stability	0.63	0.98
MOE_{2}: Seakeeping	0.58	1
MOE_{3}: Mooring and riser interaction with hull	0.92	1

All the calculated characteristic values of stability, seakeeping and mooring and riser loads are in the allowable limits which are defined by standards and regulations for both cases. Based on the results given in Table 16, cylindrical FPSO has better seakeeping characteristics. Significant response is appeared as a dominating parameter (with weight factor: 0.63) for seakeeping evaluation. Minimum Motion Sickness Dose Value (MSDV) also observed for cylindrical type. Cylindrical FPSO has lower mooring line tension and riser stresses as well.

5. Verification

To verify results of this study, the mooring lines and riser loads are calculated by both AQWA and ORCAFLEX software. Simulation time, time interval and environmental condition are assumed the same to provide identical results in both software. Yaw response amplitude of ship-shaped FPSO in AQWA and ORCAFLEX is compared as a test case. Negligible difference in the responses is observed as shown in Figure (f) in the appendix. In general, larger standard deviation is observed from AQWA as shown in Figure (f) of appendix. Therefore, AQWA results should be considered more conservative and selected as the basis for calculation of the MOPs.

6. Conclusions

In this study the response characteristics of two commonly used ship-shaped and cylindrical FPSOs, are compared. The shallow water and benign environmental condition at the full loaded draft are used as the basis for the comparison. The selected attributes for responses comparison include: stability characteristics, seakeeping performance, mooring line tension and riser stresses. The AHP method is used to rank the attributes which are used for response evaluation. The results in this study is limited to the wave induced linear response of the FPSO. FPSO hull interaction with mooring and riser systems are affected by both stability and seakeeping parameters.

Riser stresses are mainly influenced by horizontal displacements and predominantly by surge motion of the FPSO.

Mooring line tensions are affected predominantly by heave motion of FPSO. The stability characteristics of the FPSO primarily depends on water plane area, center of gravity, and displacement, draft and mass moment of inertia. Mooring line tension and riser stresses are influenced by these stability parameters.

The final conclusion of this case comparison shows that the cylindrical FPSO has better performance in stability, seakeeping and mooring tension and riser stresses which is mainly due to the hull geometry which absorbs less energy from waves.

7. References

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8. Appendix

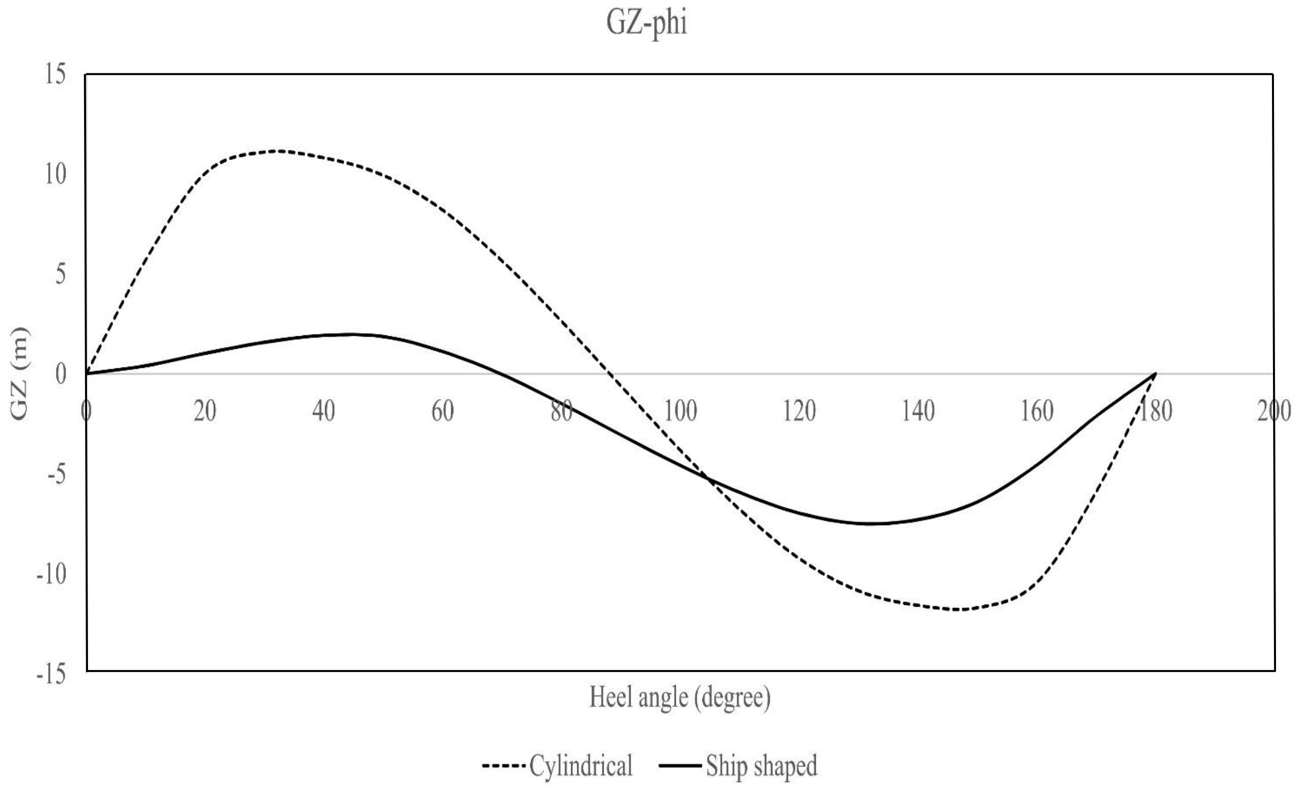

Figure (a). GZ-φ diagram

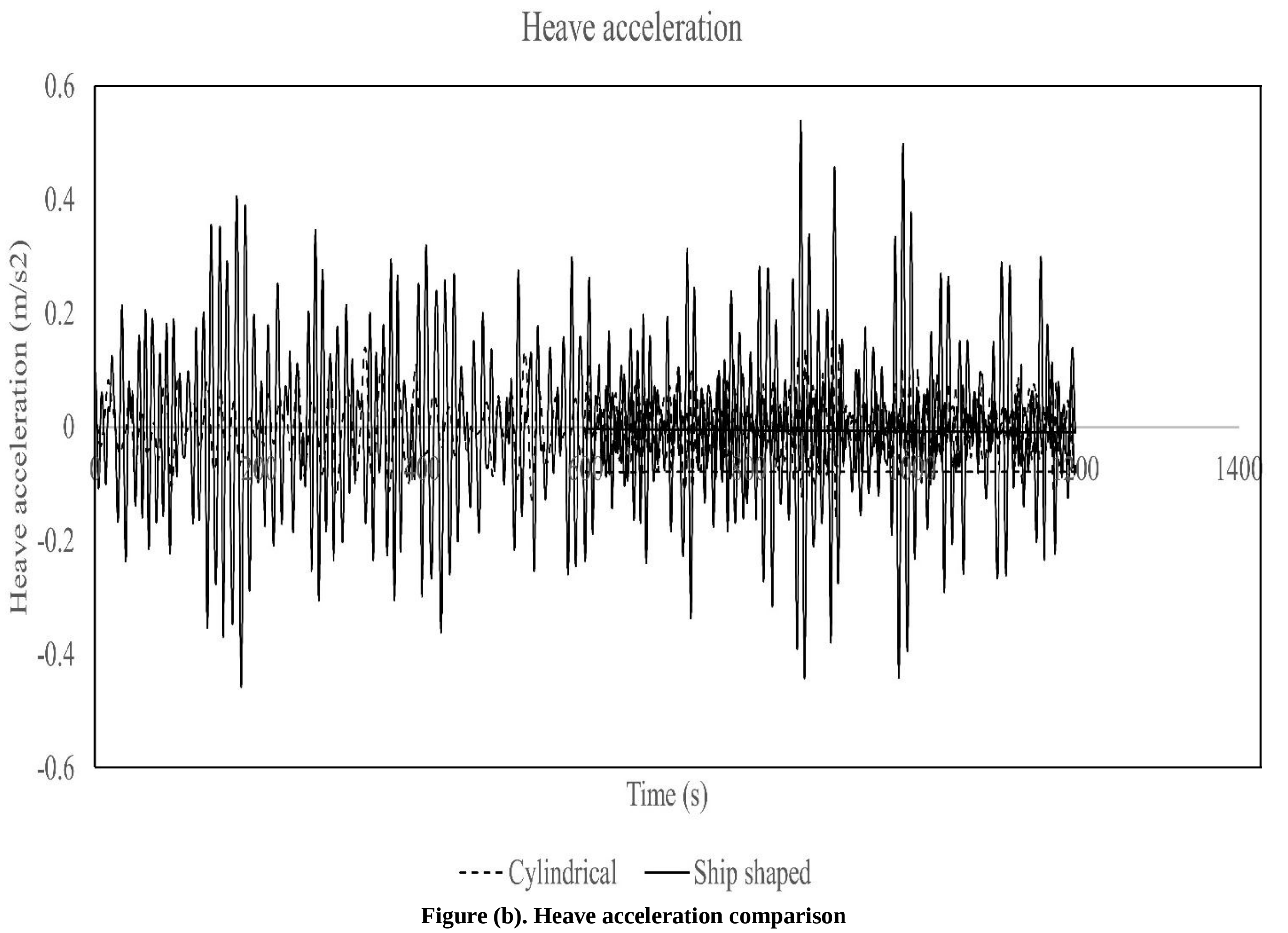

Figure (b). Heave acceleration comparison

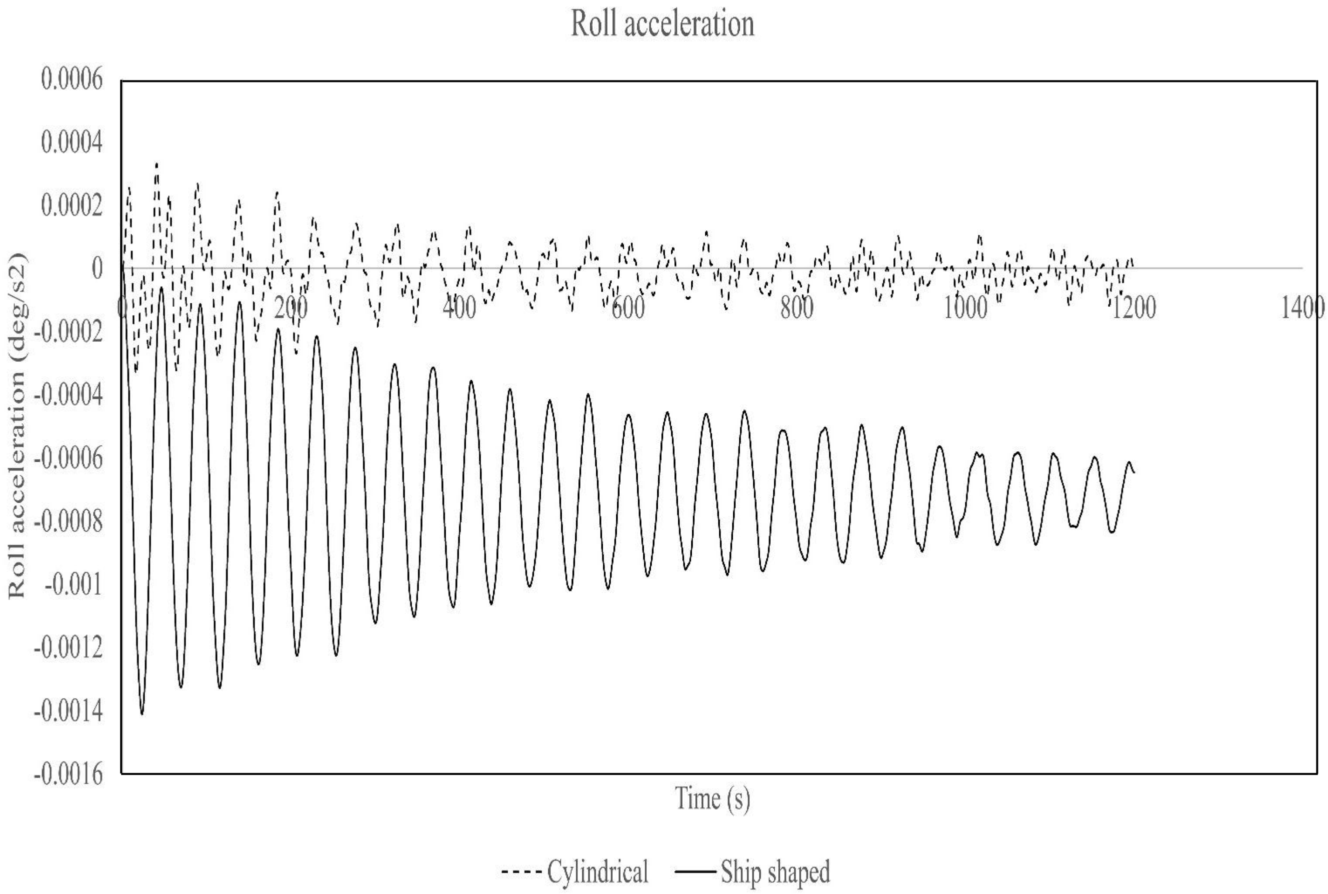

Figure (c). Roll acceleration comparison

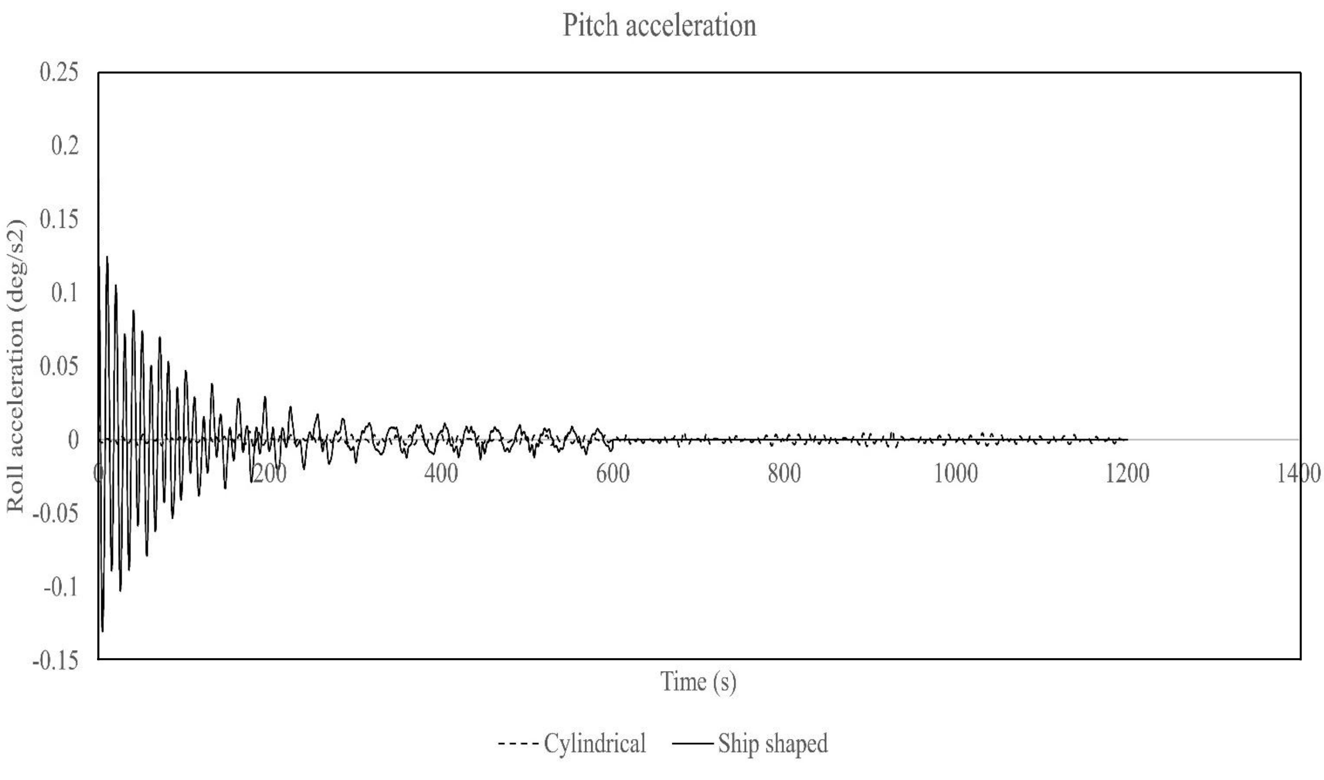

Figure (d). Pitch acceleration comparison

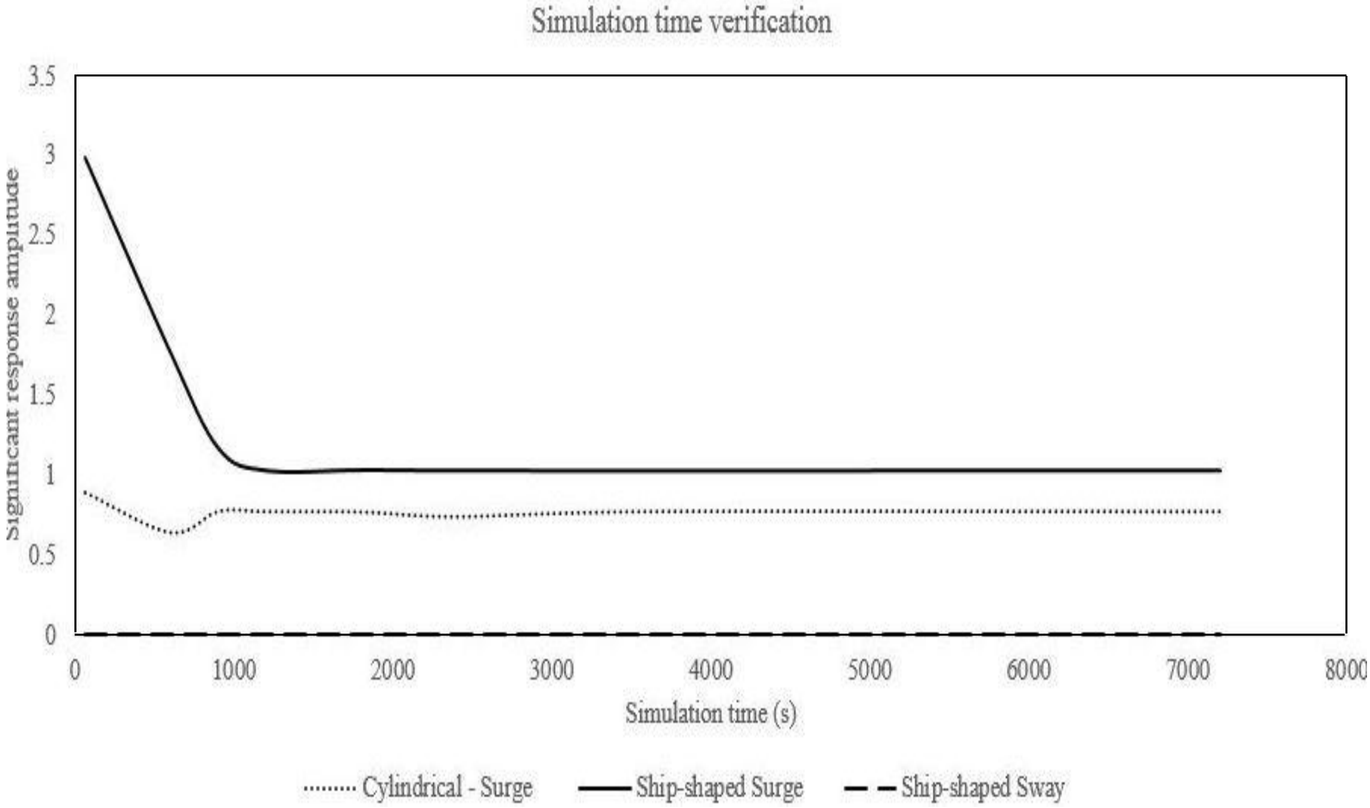

Figure (e). Simulation time verification

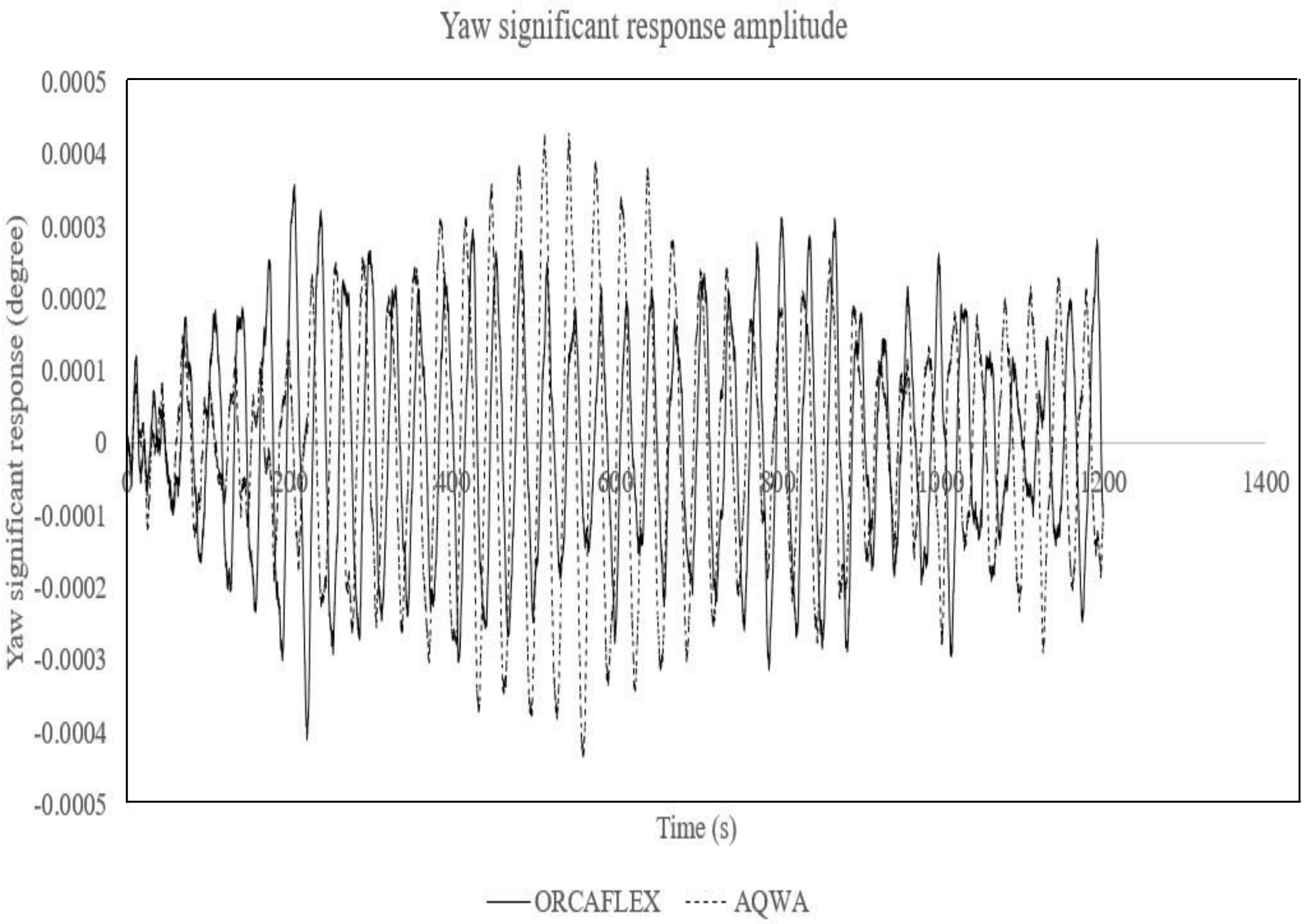

Figure (f). Results verification with two different softwares (ship-shaped yaw significant response amplitude)