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Numerical Analysis of the Effects of Sandglass-Type FPSO Hull Form on Hydrodynamic Performance in Regular Waves

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Abstract: This paper presents a numerical investigation on hydrodynamic performance of sandglass-type FPSO with different parameters. In order to estimate the hydrodynamic performance and utilize the results on the design stage of FPSO, a frequency-domain numerical simulation program, ANSYS/AQWA software package was used. Numerical studies were conducted to investigate the heave and pitch motion responses of sandglass-type FPSO. Eight different inclination angles were utilized with the same displacement and draft. The effects of different inclination angles including different radii of underwater radius of floating object on hydrodynamic responses and forces that acted on FPSO were investigated and presented here. Numerical results were compared against experimental data of a sandglass-type model, and good agreement was achieved in small amplitude regular wave cases. Based on the simulation results, it was concluded that a sandglass-type FPSO with inclination angle of 45º proposes proper hydrodynamic performance in heave and pitch motion for all ranges of wave frequencies. Also as it was predicted, the effect of heading sea on sandglass-type FPSO was significant compared to other wave directions.

Keywords: Regular wave, Potential theory, ANSYS AQWA, FPSO

1. Introduction

Floating Production, Storage and Offloading or FPSO is a floating vessel located near an oil platform where oil is processed and stored until it can be transferred to a tanker for transporting. FPSO is useful in newly established offshore oil regions where there is no pipeline infrastructure in place, or in remote locations where building a pipeline is cost-prohibitive. Also, once an oil field has been exhausted, the vessel can be moved to another location.

The first design of FPSO was based on classical ship-shaped vessels. But its slender and non-axisymmetric shape presented significant bending loads due to hogging and sagging. Ship shape was also less efficient in storage volume per plated area. To overcome these shortcomings associated with using traditional ship-shaped vessel for FPSO, the industry is now developing simple shapes of them. These types of FPSOs are being designed to have similar motion characteristics from all directions. Nevertheless, simple shapes like cylindrical form still have some motion problems. The heave natural frequency of cylindrical floating body is located in the bandwidth of high wave energy and thus the heave motion response is very large. Furthermore, the floating model with cylindrical shape easily triggers vortex-induced vibration and has relatively smaller deck area.

Many experimental and numerical studies have been carried out to examine the effects of FPSO's hull form on hydrodynamic performance in regular and irregular waves. Wichers [1] in 1988 initiated a comprehensive study for numerical simulations of a turret moored FPSO in irregular waves with wind and current. He derived the equations of motion of such model in the time domain using an uncoupled method and solved rigid body and mooring line dynamics separately. In 2001, Heurtier et al. [2] compared the coupled and uncoupled analysis for a moored FPSO in harsh environments and suggested that the uncoupled analysis results are efficient to be used in the early design phase of the mooring system. Pascoal et al. [3] studied hydrodynamic behavior of OCTOPLUS type of FPSO with eight columns under deck experimentally in regular and irregular waves and compared the results with numerical results. They found that this type of FPSO has very small motions in all degrees of freedom due to small water plane area. Kim et al. [4] developed a time domain based package for simulating the global motion of a turret moored FPSO. They also conducted physical model tests to study the vessel motion and mooring tension for non-parallel wind, wave, current and 100 years hurricane condition in Gulf of Mexico. Hong et al. [5] investigated the dynamic performance of LNG-FPSO by a time domain numerical simulation program. Chen et al. [6] studied the dynamic response of a tanker based FPSO using DNV's software (SEFAM) in deep water. Large amplitude of motion has been observed in this type of FPSO. Nishanth et al. [7] performed an uncoupled hydrodynamic analysis using Sesam HydroD software to study the response of ship-shape FPSO under the action of unidirectional random waves in Malaysian waters in operating conditions. They used diffraction theory to calculate the wave load on FPSO and Airy's linear wave theory to calculate the fluid particle velocity and acceleration. In the same year, Nam et al. [8]

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investigated berthing problem between a FPSO and a shuttle tanker in wave. The classical finite element method in time domain was employed to solve the Laplace equation in fluid domain and the characteristics of the motion responses in berthing operation were examined with various wave frequencies, berthing speeds and wave headings.

In recent year, sandglass-types of FPSO have been presented as an attractive form for the improvement of hydrodynamics performance in rough seas. It has not only larger spaces of oil storage than traditional ocean platforms, but also has better hydrodynamic performance and adaptability to extreme sea environment. A new concept of floating body with an innovative sandglass-type was presented by Huang et al. [9, 10, 11] in 2013. They investigated the new model of FPSO with sandglass- type and presented the advantages of this new model versus conventional ship-shape and cylindrical FPSO. Also, Yao et al. [12] in 2014 studied the heave and pitch motion performance in wave for the sandglass-type model by potential flow boundary element and spectrum analysis methods in frequency domain. Furthermore, the variable displacement method was used to calculate the statically stability curve. Finally, by comparing with the cylindrical floating body model of Sevan Marine Company in Norway and octagonal floating body model of CNOOC in China, it was found that the design of sandglass shape could obviously improve the stability and hydrodynamic characteristic of FPSO. In the same context, Vijayalakshmi and Panneerselvam [13] investigated hydrodynamic characteristic of a 1:45 scaled model of a sandglass-type FPSO with nine-sided cross section in the icy water of the Arctic numerically and experimentally. They also studied the effect of damping plate on motion response of the mentioned FPSO. Novel FDPSO sandglass-type floating body was studied by Yu-xin et al. [14]. They investigated the effect of different mooring system parameters on FDPSO motion in deep water. They used CFD software to investigate the effect of nonlinear wind and current on FDPSO and compared the results with Det Norshke Veritas (DNV) requirements. Wang, Ye et al. [15] in 2015 investigated a new sandglass-type FDPSO in order to enhance the hydrodynamic performance of traditional ship-type and cylindrical FDPSO by classic BEM and mathematical Deduction methods based on wave potential theory. They used Potential flow theory and engineering estimation methods to theoretically and mathematically deduce the wave excitation force, added mass and corresponding frequency for the minimum RAO of heave motion for the new sandglass-type model. In addition, corresponding frequency for the minimum RAO was chosen as control variable to design shape parameters and thus minimize heave motion response. Compared with FPSO, the FDPSO denotes an addition of drilling rigs and thus, the relevant floating models have a cylindrical moon-pool structure with various radii. Therefore, the heave motion characteristics of different FDPSOs were simulated by BEM. Finally, the heave motion of sandglass-type FDPSO was compared with ship-shape and cylindrical ones. Wang, Du et al. [16] in 2016 studied FPSO by using classical boundary element method based on wave potential theory, and the effects of shape parameters on motion performance of sandglass-type model were examined. Hydrodynamic performance of floating body was determined by two shape parameters of inclination angle and middle part radius of the structure. Thus various floating models with different inclination angles and middle part radii were created to study the effects of shape parameters on motion performance of sandglass-type model. In that study, the displacement was constant.

In this paper, numerical simulation of sandglass-type FPSO is conducted under the effects of small amplitude regular waves. To accomplish this task, frequency-domain numerical simulation program, ANSYS AQWA software is used. Current numerical results of heave and pitch motions in case of cylindrical FPSO are validated by experimental data of Wang, Du et al. [16]. The effects of hull form parameters on linear motions of sandglass-type model are studied and optimized structure parameters are presented. In addition, the effects of wave directions on sandglass-type FPSO motions are studied.

2. Governing Equations

Although there are different methods to analyze floating bodies in waves, it is possible to get a suitable result by using linear analysis. Of course, in order to investigate the floating body response in a short time, a linear method in moderate marine conditions provides an acceptable answer. In order to investigate the floating response in waves, using the average-Reynolds-Navier-Stokes method which considers viscosity and real wave condition, provides a more appropriate response than the potential method. However, by using a series of assumptions and simplifications in the problem, such as considering the low speed of floating body and the small amplitude of wave, a potential method can be used to find an appropriate and approximate response. ANSYS-AQWA is a powerful, fast and accurate software at zero or low speed and for a floating object with simple geometry and moderate marine conditions. Therefore in this paper, we can analyze the structural motions correctly by using the potential method based on the ANSYS-AQWA software. Under traditional assumption, the fluid is inviscid and incompressible, and the flow is considered to be irrotational and all viscous shear forces are neglected, so the fluid domain is governed by the velocity potential φ satisfied by Laplace equation [15, 16]. These equations and boundary conditions are as follows:

Continuity:

$$\nabla^2\varphi = \frac{\partial^2\varphi}{\partial x^2} + \frac{\partial^2\varphi}{\partial y^2} + \frac{\partial^2\varphi}{\partial z^2} = 0 \tag{1}$$

Kinematic free surface condition

$$\frac{\partial\eta}{\partial t} = -\nabla\phi.\nabla\eta + \frac{\partial\phi}{\partial z} \qquad , z = \eta(x, y, t) \tag{2}$$

Dynamic free surface condition

$$\frac{\partial \phi}{\partial t} = -g\eta - \frac{1}{2}|\nabla \phi|^2 \quad , z = \eta(x, y, t) \tag{3}$$

Seabed condition

$$\frac{\partial \phi}{\partial z} = 0 \quad , z = -h \tag{4}$$

Body condition

$$\frac{\partial \phi}{\partial n} = \vec{v}.\vec{n} \tag{5}$$

Where φ and η represent velocity potential and free surface elevation, respectively. In addition, a proper far-field condition should be implemented to avoid the unwanted wave reflection from the downstream end of the domain [16].

$$\Delta\phi \to 0 \quad , x \to \infty \tag{6}$$

The pressure on the body, P, can be calculated by using the Bernoulli equation. The hydrodynamic forces, F, and moments, M, can sequentially be obtained by integrating the pressure over the wetted body surfaces.

$$P = -\rho\left(\frac{\partial \phi}{\partial t} + \frac{1}{2}\nabla\phi.\nabla\phi + gz\right) \tag{7}$$

$$F = \iint_S P.nds \tag{8}$$

$$M = \iint_S P(X \times n)ds \tag{9}$$

3. Computational model

Fig. 1 shows the schematic of sandglass-type FPSO subjected to regular small amplitude waves. The main principles of sandglass-type FPSO are presented in Table (1).

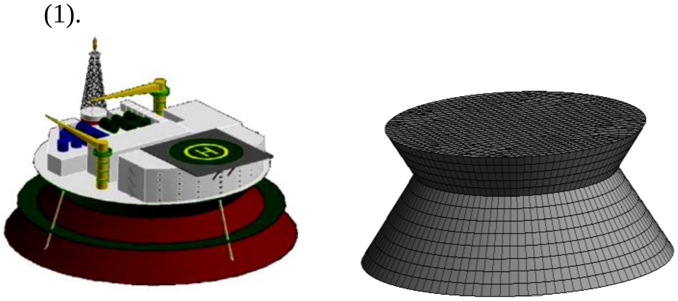


Figure 1. Hydrodynamic model of new sandglass-type FPSO [16]

Table 1. Main dimensions of sandglass FPSO

Under-water section radius	70-90 m
middle section radius	50 m
deck section radius	64.5 m
Draft	27.151 m
Freeboard	14.49 m
Displacement	358.75 Megaton
Inclination angle	30-65 degree

In this paper, the effect of variation of some underwater parameters such as inclination angle and the radius of bottom plane of structure on hydrodynamic responses of sandglass-type FPSO has been studied. The variation of inclination angles is from 30 to 65 º. The draft and displacement are constant for all structures.

4. Calculation Method

The solution method in this paper is boundary element method. The hydrodynamic behavior of sandglass-type FPSO in regular waves is calculated here by the commercial ANSYS-AQWA software which is widely used in offshore industry. ANSYS AQWA software is used for computing hydrodynamic properties, including heave and pitch motions in regular waves. It is similar to WAMIT. Both utilize a 3-D panel method for wave loads, which is based on potential flow theory. Since the unsteady motions are supposed to be small and wave amplitude is also small compared to wave length, linearized theory is applied for the present study.

ANSYS AQWA solves a set of linear algebraic equations to obtain the harmonic response of the body to regular waves. These response characteristics are commonly referred to as response amplitude operators (RAOs) and are proportional to wave amplitude. The equation of motion describes the response of the flexible structure to external excitation mentioned in Eq. (10).

$$[M_s + A]\ddot{X} + C\dot{X} + BX = F \tag{10}$$

$$\begin{cases} X = X_0 e^{-i\omega t} \\ F = F_0 e^{-i\omega t} \end{cases} \tag{11}$$

Where M_s, A, B and C denote the N×N mass, added mass, structural linear damping and stiffness matrices, respectively. The N×1 vectors X, $\dot{X}$ and $\ddot{X}$ represent the structural displacements, velocities and accelerations, respectively. The column vector F denotes the external forces and N is the number of degrees of freedom assigned to the structure.

RAO which is the ratio between FPSO motions and wave amplitudes, can be driven for heave and pitch motions as Equations (12) and (13).

$$Heave\ RAO = \frac{F_{33}}{-\omega^2(M + A_{33}) + i\omega B_{33} + C_{33}} \tag{12}$$

$$Pitch\ RAO = \frac{M_{21}}{-\omega^2(M + A_{21}) + i\omega B_{21} + C_{21}} \tag{13}$$

5. Validation

In order to verify the process of obtaining the hydrodynamic properties, the probe done experimentally for cylindrical FPSO by Wang Du et al. [16] is repeated here with ANSYS AQWA software, and the results are compared for accuracy. The model is shown in Fig. 2 and the structure parameters are presented in Table (2). All coefficients in this section are made dimensionless according to wave amplitude. The dimensionless heave and pitch motions of cylindrical FPSO are studied and the results are presented in Figure (3).

Table 2. Main dimensions of cylindrical FPSO

Maximum radius	32.575 m
Radius of main body	30 m
Draft	18.2 m
Height of floating body	27 m
Displacement	358.75 Megaton

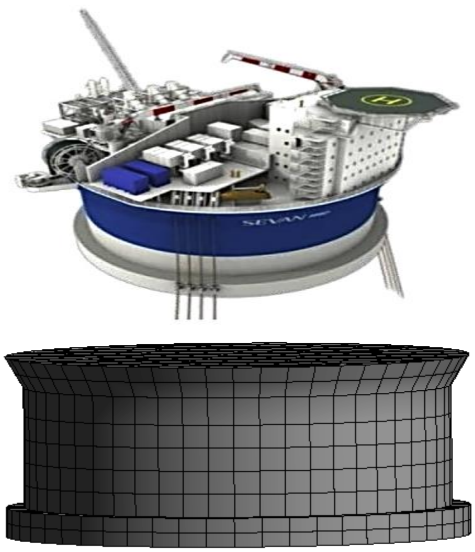


Figure 2. Schematic model of Sevan Piranema FPSO [16]

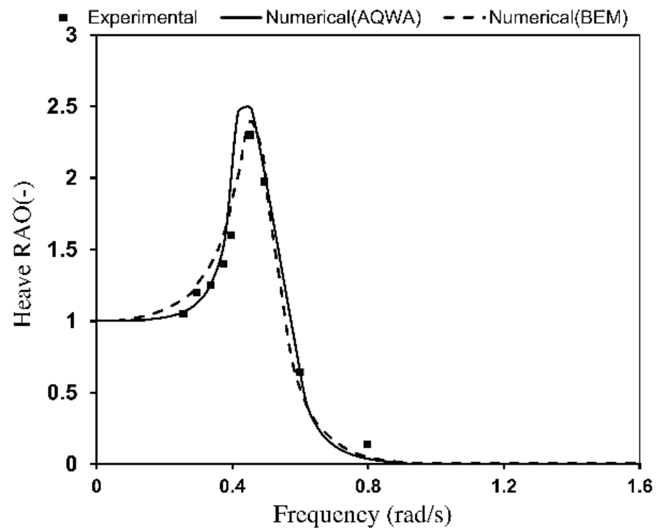
According to Fig. 3, it can be seen from the comparison of maximum amplitude of heave and pitch motion obtained by the present numerical model with those obtained by using the numerical and experimental ones that they have good agreement with each other. The derivation of maximum amplitude of motions for three methods is presented in Table 3.

From Table 3, it can be found that the differences of motion performance between the present numerical and numerical and experimental method for heave and pitch motion are less than 10%, which satisfies the engineering precision requirement and validates the accuracy of numerical method. Therefore, it is reasonable to use ANSYS AQWA software for investigating sandglass-type FPSO.

6. Numerical results and Discussion

6.1. The effect of variable underwater parameters on heave and pitch motions

All RAOs diagrams of sandglass-type FPSO have been calculated for 6-DOF (degree of freedom) and heave and pitch results in regular wave are presented in Fig. 4. These are the prominent motions of sandglass-type FPSO floating in wave with heading of 180 °.



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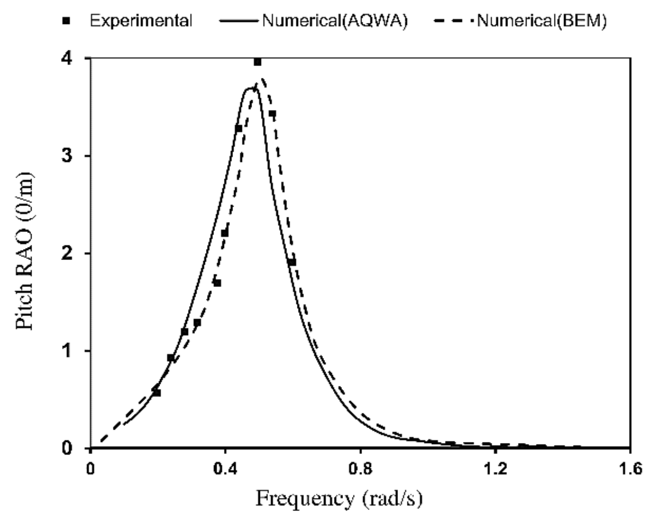
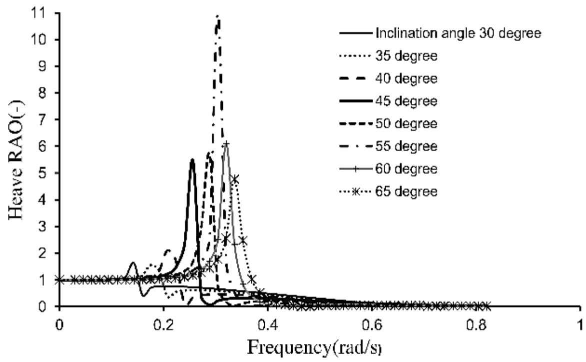


(b)

Figure 3. Comparison of experimental and numerical results- cylindrical FPSO- a. heave b. pitch

Table 3. Derivation of heave and pitch motion for three methods

Method	Heave motion response(-)	Pitch motion response(0/m)
Experimental[16]	2.30	3.959
Numerical(BEM)[16]	2.395	3.79
Numerical(AQWA)	2.476	3.65
Relative error	7.65%	-7.8%



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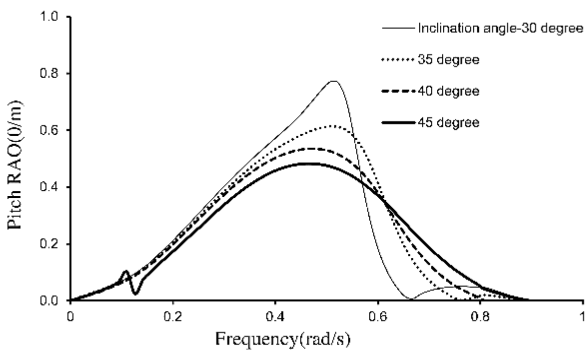

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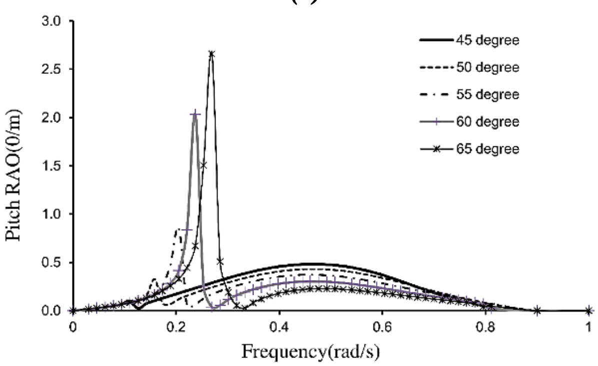


(c)

Figure 4. RAO in regular wave with 27.151 m draft: a. heave, b. pitch (30-45), c. pitch (45-65)

It is quite evident that the smallest amplitude of maximum heave motion occurs in angles lower than 45 º for inclination angle. The degree of 35 has the lowest dimensionless heave amplitude of about 1.55 and the degree of 55 has the highest of about 11. It shows that smaller inclination angles (actually angles under 45 º) have suitable responses in heave motion when they are exposed to regular waves, but they miss another important item named stability. In fact, they are not stable enough to float properly in waves (Fig. 4a). On the other hand, pitch motion analysis is a bit complex. In this paper, pitch motion behavior of structures is divided into two parts of Under 45 º of inclination angle and over it and also first and second critical frequency. In Figure 4.b., for less than 45 º of inclination angle, it is obvious that the maximum amplitudes of pitch motion in second critical frequency decrease when inclination angles increase to 45 º. In first critical frequency, the variations are negligible. For inclination angles over 45 º, responses are different. In second natural frequency, maximum amplitude of pitch motions continues to decrease when inclination angles increase, while in first critical frequency, we can perceive that variation are significant and with increase in inclination angle from 45 to 65 º, the maximum amplitude of pitch motion rises suddenly and reach 2.7. Thus, the structure does not have probable behavior in pitch motion in inclination angles over 45 º (Fig. 4.c).

Based on the current simulation results, in this paper, 45 º of inclination angle has been chosen as best for sandglass-type FPSO by considering optimum amplitude of motions and stability. In this angle, both heave and pitch motions have optimum amplitude. Consequently, for this angle, the effect of different wave directions on 6-DOF motions was examined.

6.2. The effect of wave direction on 6-DOF of optimized sandglass- FPSO

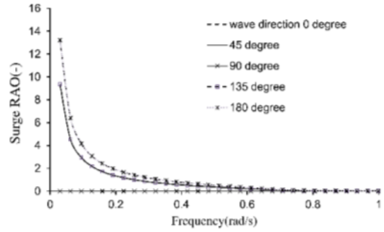
The effect of wave direction on 6-DOF of the FPSO with inclination angle of 45 º and mid-part radius of 50 m and bottom part radius of 77.15 m was examined and the results are presented in Figure 5.

As shown, wave direction does not have any significant effect on vertical motions like heave and yaw. Also, it can be deduced from the results that angular directions of waves like 45 and 135 º have smaller maximum amplitude in comparison to straight wave directions like zero, 90 and 180 º. In fact, the maximum amplitude of one motion is distributed into two motions in angular waves. In angular wave, both roll and pitch motions exist in smaller amplitude, but in straight wave direction, one of them is maximum and the other is zero.

7. Conclusion

In this paper first new type of vessel named FPSO and new type of FPSO with form of sandglass has been described. For verifying the solution method, heave and pitch motion of a cylindrical FPSO compared with results obtained by experimental method. The results determined that present numerical method can conclude appropriate response. Next, numerical simulations were carried out to study the hydrodynamics behavior of a novel sandglass-type FPSO form subjected to different conditions. For this purpose, the body motions under the influence of changing the inclination angle that changes the bottom part radius were studied. It was observed that, changing inclination angle has the greatest effect on heave and pitch motions. By analyzing both heave and pitch motions together, the best inclination angle was about 45 °. Also based on the results of the effect of wave direction on 6-DOF, it is extracted that vertical motions don't have significant variations.

All in all, it can be noted that the results obtained in this study are instrumental just for FPSOs that have these properties and different displacement, draft, center of mass and so on may get different results.



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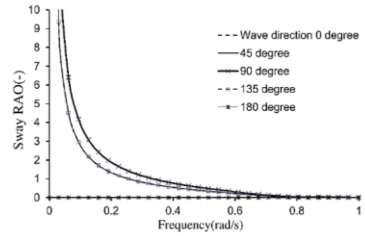

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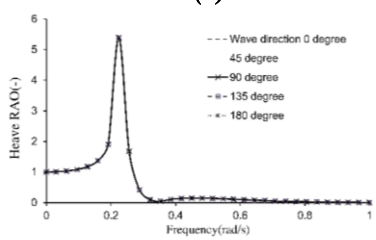

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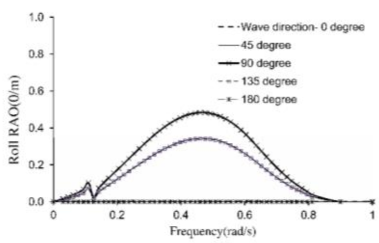

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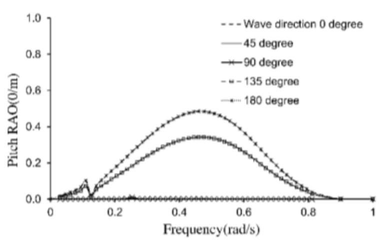

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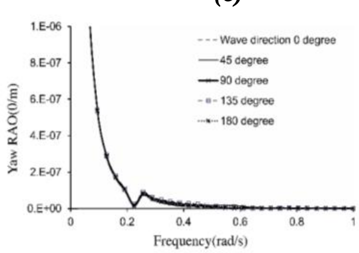

(f)

Figure 5. RAOs for 45-degree inclination angle for different wave directions, a. Surge, b. Sway, c. Heave, d. Roll, e. Pitch, f. Yaw

8. Endnotes

Symbol	Description	Unit
A	Added mass matrix	kg
B	Stiffness matrix	N/m
C	Damping matrix	
F_{ij}	Exciting force matrix	N
g	Gravity acceleration	m/s^2
h	Depth of water	m
M_s	Structure mass matrix	Kg
M_{ij}	Exciting moment matrix	N.m
n	Normal vector	---
P	Pressure	N/m^2
v	velocity	m/s
x	Longitudinal coordinate	m
y	Transverse coordinate	m
z	Vertical coordinate	m
ϕ	Velocity potential	m/s
η	Free surface elevation	m
ω	Angular velocity	Rad/s

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