HEAVE DAMPING EFFECTS DUE TO CIRCULAR PLATES ATTACHED AT KEEL TO SPAR HULL

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Abstract—Single point Anchor Reservoir (SPAR) platforms is a kind of floating platforms that are used in deep waters. These are mainly used for deep water applications for drilling, production, processing, storage and offloading of ocean deposit. The offshore spar platform is modelled as a rigid body with six degrees-of-freedom (DOFs), connected to the sea bed by multicomponent catenary cables which consist of a mooring line. The numerical model is generated in ANSYS-AQWA along with the wave actions on the structure. The response analysis is performed in frequency domain applying unidirectional regular wave model is used for computing the incident wave kinematics by Airy’s wave theory, irregular wave model is used for computing the incident wave kinematics by JONSWAP spectrum and hydrodynamic force by Morison’s equation and Froude-Kryvol wave forces. The heave motion of a floating structure is critical, the heave response can be suppressed by installing heave plates. This paper study about the response analysis of SPAR platform for five different configurations without and with lower heave plates of five different heave plate diameters (1.1, 1.2, 1.3, 1.4 & 1.5 times the diameter of SPAR hull).

Keywords—Single Point Anchor Reservoir (SPAR), Heave damping plates, ANSYS AQWA, Irregular wave model

I. INTRODUCTION

Exploration of oil and gas resources has been accelerated towards deeper waters due to depletion of their reserve in shallow water depth. Due to ever rising demand for oil and gas in the world today, the global offshore oil and gas industry has been growing by leaps and bounds. SPAR technology has been utilized for offshore structures such as research vessels, communication relay stations, and storage and offloading platforms. Several advantages of the classic SPAR compared with other floating platforms are including structural simplicity, low motions in moderate and extreme ocean waves, good protection of riser connections to the sea bed, and low cost. Additionally, the enclosed cylinder acts as protection for risers and equipment, making SPARs an ideal choice for deep-water developments. Therefore the SPAR is an attractive design solution for regions where the environment is harsh. However, the SPAR platform undergoes large heave motions at resonance, up to 8–10 times of incident wave amplitude. Such large heave motions can affect the restoring moment of pitch, and it starts to vary with time in phase with the heave motion.

This paper will focus on (i) Developing a preliminary design for the SPAR platform with a hull and ballast at bottom for stability at deeper waters for normal offshore platform drilling loading conditions. (ii) To model the SPAR platform along with catenary mooring lines using ANSYS AQWA software and study the responses of SPAR without waves, with the presence of both regular and random waves of different wave directions ranging from 0° to 180°. (iii) And also to study the responses of design SPAR platform with different heave plates of different diameters 44.57m, 48.63m, 52.676m, 56.728m and 60.78m and having the common thickness of 0.07m in regular waves and random waves. (iv) Compare the responses of SPAR without heave plate and with heave plate of five different dimensions of heave plate. (v) To determine the hydrodynamic forces such as Froude-krylov wave forces, Morison drag forces on structure and total forces. (vi) The motion response of the structure will be undertaken using a diffraction program, ANSYS AQWA.

Glanville, et al., (1991) [1] gave details of the concept, construction, and Installation of offshore SPAR platform. Mekha, et al., (1995) [2] modelled the offshore SPAR platform with three
DOFs, i.e., surge, heave, and pitch, and used constant inertia coefficient, $C_m$, as in the standard Morison's equation, or used a frequency-dependent $C_m$ coefficient based on the diffraction theory. The drag forces were computed using the nonlinear term. Kurian et al., (2012) \(^{[3]}\) performed both numerical and experimental studies on the dynamic responses of classic and truss SPAR platforms considering random wave and current forces. The damping ratio and natural periods of the system were obtained using a free decay test and the response amplitude operators (RAOs) were calculated for heave, surge, and pitch motions. It was concluded that coupled wave and current forces would result in higher surge, heave, and pitch responses for the classic SPAR compared to the truss SPAR. The heave response of four different configurations of the damping devices was investigated by Tao and Cai (2004)\(^{[4]}\) both numerically and experimentally, which led to the observation that a cylinder with a thin circular plate attached to the keel yields the lowest heave response.

A floating structure will experience six degrees of freedom when exposed to wave excitation. Theses motions can be categorized as either translation or oscillatory angular motions, translations motions are the heave, surge and sway whereas the angular motions consist of roll pitch and yaw (Faltinsen 1993), the six degrees of freedom can be visualized in Figure 1.1. In order to enhance the damping mechanism, during the resonant oscillation of the SPAR in the vertical direction, additional damping devices are introduced externally. A typical example of these damping devices is a heave plate, which is attached to the keel of the SPAR as shown in Figure 1.2

**Figure 1 Six degrees of freedom (Chakrabarti 1987)**

**Figure 2. Heave added mass of SPAR with heave plate**

**II. MODELLING AND NUMERICAL ANALYSIS**

Here design of SPAR platform for water depth 914.4m is studied. The main objective of the study is that to study offshore hydrodynamic analysis using ANSYS AQWA software and minimize and compare the heave effects by providing external devices like heave damping plate and determine the influence of marine growth on the structure here the study is conducted on the response of the designed SPAR platform and its effect of mooring on platform. The structure is located in North Sea, the water depth for the region is 914.4m and environmental factors like site wave height of 7m and for time period of 12.5sec are fixed as preliminary input. Preliminary design is performed from these values by doing many iterations to satisfy the criteria. If the criteria is satisfied, go to dynamic analysis which consist of two parts. One is Eigen value analysis and the other is Non-linear time domain analysis. From this analysis we form results and then lead to conclusion.

**Figure 3 .Methodology**
Parametric study: In order to determine the sizing for the main column and heave plates in this structure, a parametric study was undertaken, where a number of different size heave plates were analyzed. The main criteria for the parametric study are to achieve a reduction of heave, pitch and roll motions. The second part of the parametric study was to determine the effects of heave plates had on the motion response of the structure. Two heave plate diameters, 1.1, 1.2, 1.3, 1.4 and 1.5 times larger than the diameter of the selected columns were analyzed in the parametric study. But before proceeding to parametric study the basic stability check should performed, if the Metacentric height is positive so structure is stable. Preliminary dimensions of SPAR are shown in Table2.1.

Table2.1. Preliminary dimensions of SPAR

| SPAR elements                        | Values       |
|--------------------------------------|--------------|
| Wall thickness                       | 0.04m        |
| Freeboard                            | 16.24m       |
| Top enclosure plate thickness        | 0.04 m       |
| 1st, 2nd, 3rd and 4th Compartment plate thickness each | 0.04 m       |
| Ballast thickness                    | 52 m         |
| Bottom enclosure plate thickness     | 0.05 m       |
| Top platform thickness               | 1m           |
| Total height of structure            | 216.4 m      |
| Outer diameter of SPAR               | 40.52 m      |
| Inner diameter of SPAR               | 40.44 m      |
| Density of body (steel)              | 7.85 t       |
| Draft of SPAR                        | 198.12 m     |
| Length of platform x Width of platform| 65m x 65m   |
| Distance B/W 2nd and 1st Compartment | 45 m         |
| Distance B/W 3rd and 2nd compartment | 40 m         |
| Distance B/W 4th and 3rd Compartment | 40 m         |
| Distance B/W Ballast and 4th Compartment | 40 m       |
| Depth of hull                        | 214.31 m     |
| Density of ballast                   | 2.5 t        |
| Wave period (s)                      | 12.50 sec    |
| Wave height (m)                      | 7.00         |
| Drag coefficient (C_d)               | 0.75         |
| Drag coefficient (C_m)               | 1.0          |
Final design:
A conceptual design for offshore structure has been developed. A classic SPAR having a single vertical cylinder of outer diameter 40.52m supporting a deck of 65m *65m having draft of 198.12m and water depth of 914.4m. SPAR is connected to the sea bed by multicomponent catenary cables which consist of a mooring line of 0.0032m² cross-sectional area with taut mooring. The height of fairlead point of 808.8m is provided from seabed. A fairlead point allowed to move in the horizontal and vertical directions. The offshore SPAR platform and the cable system are treated as a single unit, and the analysis is carried out for the six DOFs as shown in below figure2.3. SPAR consists of one top enclosure and one bottom enclosure and four compartments equally spaced and weighted at the bottom by a chamber(ballast) filled with a material that is more dense than water (wet sand) to lower the center of gravity of structure there by provide stability.

![Figure 5. Schematic elevation of offshore SPAR platform](image)

III. NUMERICAL MODELLING OF SPAR

This section of the report provides a description of the program and the process of conducting a simulation. The initial step in the simulations is to calculate the free-floating RAOs using AQWA Line. Since the classic SPAR structure is symmetrical about the x and y-axis, it is advantageous to only analyze wave heading from 0 to 180 degrees with a series of intermittent headings at 45 degrees as shown in fig2.4 and 2.5.

![Figure 6 SPAR model in ANSYS-AQWA workbench module](image)  ![Figure 7 Meshed SPAR model in ANSYS-AQWA workbench module](image)

AQWA NAUT and AQWA-DRIFT setup: The next step in the analysis procedure is to run the time domain simulations using AQWA-NAUT. For this stage of the analysis, the mooring system is also specified. Environmental parameters are also required by the program, for the analysis in question, if in regular wave’s wave amplitude of 3.5m, wave direction, and time period need to specify. For random (irregular) waves AQWA-DRIFT is used, for this mooring system has to specify
Numerical investigation of SPAR with heave damping plate: Numerical simulation of hydrodynamic response of SPAR with and with heave plates of various diameter ratios from 1.1 to 1.5 has been carried out in frequency domain using hydrodynamic software package called ANSYS AQWA. The simulated 3D surface is shown in Figure 2.8. The free-floating RAOs using AQWA Line shown in figure 2.7 The next step is to simulate is to calculate the dynamic equilibrium using AQWA-LIBR (static and dynamic). Then the simulated surface is exported to time domain program called AQWA-NAUT to obtain recalculated RAO (considering mooring line stiffness) together with significant tensions in the mooring line. Numerical simulation of response and mooring line forces for the SPAR with and without heave plate has been carried out for various diameter ratios from 1.1 to 1.5.

IV. RESULTS AND DISCUSSIONS

The present study considered the modelling of two different cases of a classic SPAR (i) SPAR of diameter 40.52m without heave damping plate (ii) A classic SPAR having bottom heave plate of five different disk diameter ratio ($D_H/D_s$) of 1.1, 1.2, 1.3, 1.4 and 1.5 The above two cases were analysed for static analysis and dynamic analysis. The analysis was carried out for two different cases. The above discussed cases were analysed for regular waves in five different directions ranging from $0^\circ$ to $180^\circ$ and for random waves by considering JONSWAP spectrum. Compares the heave, roll, pitch responses of bare cylinder and with bottom heave damping plates. Compare the various
hydrodynamic forces acting on SPAR in above cases. The results obtained from the above model analysis are discussed.

4.1 Responses of SPAR structure in static condition:

4.1.1 Comparison of heave response in static condition with and without heave damping plate:

A classic SPAR of hull diameter 40.52m was analysed in AQWA for static equilibrium condition by considering no wave condition the uncoupled responses of free floating RAO’s were presented in figure 3.1. From the figure 3.1 it can be observed that the heave (z-direction) response that is 4.71 dominates the surge (x-direction) response 1.0415 and sway (y-direction) response of $1.007 \times 10^{-7}$. To minimize the heave effect heave damping plate should be provided.

Table 4.1. Hydrodynamic characteristics (free floating heave RAO’s) of SPAR models obtained from numerical modelling

| Models                         | Heave natural period (sec) | Heave added mass (kg) | Heave amplitude | Change (decrease) in heave response % |
|-------------------------------|---------------------------|-----------------------|-----------------|--------------------------------------|
| Without heave plate           |                           |                       |                 |                                      |
| With heave plate of 44.75m at keel | 27.43                     | 15100000              | 2.2387          | 53.07                                |
| With heave plate of 48.63m at keel | 27.55                     | 19700000              | 1.911           | 59.945                               |
| With heave plate of 52.67m at keel | 27.80                     | 25000000              | 1.660           | 65.206                               |
| With heave plate of 56.72m at keel | 38.07                     | 31200000              | 1.615           | 66.196                               |
| With heave plate of 60.78 m at keel | 38.31                     | 38500000              | 1.470           | 69.188                               |

Figure 11. Free floating RAO’s in x, y and z directions

Figure 12. Comparison of Free floating Heave RAO of SPAR without heave plate and with heave plate o 1.1, 1.2, 1.3, 1.4 and 1.5 times diameter

4.2 Responses of SPAR structure in dynamic condition:

A classic SPAR of hull diameter 40.52m analysed in AQWA for dynamic equilibrium condition by considering regular wave condition of wave height 7.0m and time period of 12.5seconds for the wave directions ranging from 0° to 180°.

4.2.1 Comparison of heave response in dynamic condition (regular waves) with and without heave damping plate:

The comparison of RAO based positions in X and Z-directions in different wave directions ranging from 0 to 180° of SPAR without heave damping plate and with heave damping plates of different plate diameters of were presented in graphs from figure 3.3 to figure 3.5 it shows Comparison of RAO based Positions in Z- Direction of SPAR Without heave plate and with heave plate of different plate Diameter in different directions of wave. from this figure it can be observed
that the RAO based Positions in Z-direction is more for SPAR without heave damping plate and little for the SPAR with heave damping plate of 60.78m in diameter, by increasing size of heave damping plate, the RAO based Positions in Z-Direction can be suppressed more.

**Table 4.2.** Hydrodynamic characteristics (RAO based Positions in Z-Direction) of SPAR models obtained from numerical modelling.

| Models                                      | Heave added mass (kg) | RAO based Positions in Z-Direction (m) | Change (decrease) in heave response % |
|---------------------------------------------|-----------------------|---------------------------------------|--------------------------------------|
| Without heave plate                        | -                     | 12.535e-3                             | -                                    |
| With heave plate of 44.57m at keel          | 1.1                   | 7.655e-3                              | 38.93                                |
| With heave plate of 48.63m at keel          | 1.2                   | 6.84e-3                               | 45.43                                |
| With heave plate of 52.67m at keel          | 1.3                   | 5.96e-3                               | 52.45                                |
| With heave plate of 56.72m at keel          | 1.4                   | 4.54e-3                               | 63.78                                |
| With heave plate of 60.78m at keel          | 1.5                   | 3.645e-3                              | 70.921                               |

![Figure 13](image13.png) Comparison of RAO based Positions in Z-Direction of Without heave plate and with heave plate of 1.1, 1.2, 1.3, 1.4 and 1.5 times Diameter

![Figure 14](image14.png) Comparison of RAO based positions in Z-direction of without heave plate and with heave plate of 1.5 times diameter

![Figure 15](image15.png) RAO based position with different wave directions in Z-direction

### 4.3. Hydrostatic and hydrodynamic forces:

Hydrostatic pressure results from the weight of the fluid column above the point at which (generally at bottom) that pressure is measured for SPAR structure without and with heave plate of different plate diameters.
Hydrodynamic forces:
Morison drag force for SPAR structure at three translated and rotational directions were presented in figure 3.6 and figure 3.7 respectively. From which Morison drag force is more in order of X-direction, Z-direction and Y-direction respectively and more about Y-axis. Figure 3.8 Shows Morison drag force in X-direction for SPAR without and with heave damping plate of different heave diameters of 44.575m, 48.63m, 52.76m, 56.72m and 60.78m, from which drag force is more in order of SPAR without heave plate and with heave plate of 44.575m, 48.63m, 52.76m, 56.72m and 60.78m Figure 3.9 shows Morison drag force in X-direction for different wave directions ranging 0° to 80° at an interval of 45° from this figure it can be concluded that Morison drag force is more at wave direction of 0°.

Table 4.3: Hydrodynamic forces (Morison drag force) of SPAR models obtained from numerical modelling

| Models Name | Heave added mass (kg) | Morison drag force | About Y-axis (kN·m) |
|-------------|-----------------------|-------------------|---------------------|
| Without heave plate | -                      | 293.3, 121.01     | 41600               |
| With heave plate of 44.575m at keel | 1510000               | 249.482, 121.21 | 34900               |
| With heave plate of 48.63m at keel | 1970000               | 207.44, 121.31 | 32200               |
| With heave plate of 52.67m at keel | 2500000               | 205.22, 121.34 | 32100               |
| With heave plate of 56.72m at keel | 3120000               | 204.19, 121.443 | 32000               |
| With heave plate of 60.78 m at keel | 3850000               | 203.238, 154.83 | 31900               |

Figure 16. Morison drag force in X, Y and Z directions
Figure 17. Morison drag force about X, Y and Z directions.
Figure 18. Comparison of Morison drag force in X-direction for SPAR without heave plate and with heave plate. Direction in different wave directions.
4.4 Random (irregular) waves:
A classic SPAR of hull diameter 40.52m analysed in AQWA for dynamic equilibrium condition by considering random wave condition by using JONSWAP wave spectra.

4.4.1 Comparison of heave response in dynamic condition in irregular waves with and without heave damping plate:
The figure 3.6. Comparison of wave frequency position in z-direction of SPAR Without heave plate and SPAR with heave plate of different diameters and hydrodynamic characteristics summarized in Table 3.4., increase in heave damping over the SPAR without heave plate is maximum for the SPAR with heave plate of 60.78m in diameter configuration (67.18% increase), followed by plate of 56.72m, 52.76m, 48.63m, 44.575m diameter.

Table 4.4. Hydrodynamic characteristics (wave frequency position in Z- Direction) of SPAR models obtained from numerical modelling.

| Models               | Heave added mass (kg) | wave frequency position in Z-directions in meter | Change (decrease) in heave response % |
|----------------------|-----------------------|-------------------------------------------------|---------------------------------------|
| Without heave plate  | -                     | --                                              | -                                     |
| With heave plate of 44.575m at keel | 1.1 | 15100000 | 15.9469 | 27.34 |
| With heave plate of 48.63m at keel | 1.2 | 19700000 | 8.9432 | 59.25 |
| With heave plate of 52.67m at keel | 1.3 | 25000000 | 7.5298 | 65.68 |
| With heave plate of 56.72m at keel | 1.4 | 31200000 | 7.5073 | 65.89 |
| With heave plate of 60.78 m at keel | 1.5 | 38500000 | 7.2032 | 67.18 |

Figure 19. Comparison of wave frequency position in z-direction of SPAR Without heave plate and SPAR with heave plate of 44.57m, 48.63m, 52.67m, 56.72m and 60.78m diameter

V. CONCLUSIONS
Two different cases of a classic SPAR (i) SPAR of diameter 40.52m without heave damping plate (ii) A classic SPAR having bottom heave plate of five different disk diameter ratio (D_d/D_s) were studied. Numerical simulations were conducted in frequency and time domain using AQWA to
analyses the motion response of the structure in static condition (no waves), with five different wave directions of regular waves and random waves. The main conclusions from this study are as follows:

- In static condition heave response is critical for SPAR. To suppress the heave effect, heave damping plates of same thickness with varying diameters provided. By increasing size of heave damping plate, the heave response can be suppressed more maximum of 69.18% for static condition and 70.2% for dynamic condition.
- In dynamic condition the suppression of RAO based positions in Z-directions also increased with increase in diameter of heave plate. RAO based position in X-direction next predominant to Z-direction, it is more at wave direction of 1800, it can also suppress with presence of heave plate. Hydrodynamic forces Morison drag force is more in X-direction and about Y-axis, and more at wave direction of 00.
- In random wave conditions wave frequency position is more predominant can also be suppressed with presence of heave plates.

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