Experimental study on heave damping due to the heave plate addition on the SPAR keel

Murdjito1, B Ali2, F Ardhianutama1, E B Djatmiko1, N Syahroni1, Y Mulyadi1, R D Riyanto1, R W Prastianto1, Handayani1 and I Rochani1

1 Department Ocean Engineering, Faculty of Marine Technology, Institut Teknologi Sepuluh Nopember, Surabaya 60111, Indonesia
2 Indonesian Hydrodynamics Laboratory, Agency for the Assessment and Application of Technology, Surabaya 60111, Indonesia

Abstract. Recent years have shown the increasing number of SPAR offshore floating platforms built and delivered worldwide. This eventually is strongly related to the generic potential of such platforms, in term of economy and performance aspects, especially for the operation in deep water. For operation in harsh sea environment previous SPAR investigations suggested the addition of heave plate on its keel to enhance the heave motion quality. This paper reports an experimental study conducted on SPAR model, scaled 1: 125 from the full size, installed with a heave plate sized 1.3 of hull diameter. Results of the study demonstrate the additional of heave plate may reduce the heave reaction force due to wave excitation approximately 35% in comparison with that without heave plate. This in turn leads to the decreasing of heave response by as much as 54%. Evaluations suggest the reductions in heave reaction force and response are induced by the escalation of heave damping in the order of 49% generated by the heave plate. The experimental results are well verified by the outcomes of computations based on analytical method and strip theory.

1. Introduction

Along with the development of offshore oil and gas exploration and exploitation, fixed offshore platforms are not considered economical anymore when compared to floating platforms that can move from one to another location [1]. One of the factors that influence the effectiveness of a floating system operating at sea is the factor of safety. So the design capability is needed to predict the behavior and survivability of floating offshore platforms when extreme seas must be faced [2]. One type of floating offshore platform that recently has an increase in demand is Single Point Anchored Reservoir or well known as the SPAR [3].

Offshore structures are strongly affected by several environmental load conditions such as wind, waves, and currents [4]. Due to these loads, SPAR structure will move beyond its performance competency. To minimize it, the SPAR is moored mostly using a catenary mooring system with six to twenty ropes tethered to the seabed. The main function of the mooring is to keep the floating structure in the planned position. The classic SPAR natural heave period is generally relative long, which is around 25 to 30 seconds. This is due to the damping amplitude in the SPAR vertical body which is not too significant. Therefore classic SPAR shows a reliable design solution for oil and gas exploration activities in less extreme sea areas and of course, there are abundant oil reserves [5].

In order a SPAR could operate in more severe seas, it must have the ability to enhance the heave motion quality. It is not enough a SPAR structure has a deep draught only to increase the level of heave damping and hence decrease the heave motion. In this respect a heave plate is an alternative solution as
heave damping additions to reduce heave motion so that if the SPAR system is installed with risers, then the risers will be safer due to the minimum heave movement. The heave plate that added to SPAR keel, not only has an impact of the heave damping and motions, but also increases the added mass of the system.

In another study by Jain and Agrawal [6], the stiffness and damping of the SPAR platform with the catenary mooring system were analyzed using the Airy wave theory and Morison force. The study concluded that the mooring system significantly affected the motion responses. Then Jameel et al. [7] investigated the effect of mooring drag and inertia on the response of SPAR platform. This study conclude that the configuration of mooring lines affected drag and inertia forces due to hydrodynamic damping.

The motion response from the SPAR Platforms is an important aspect to be comprehended. The design concept behind SPAR draught which is sufficiently deep is to reduce the heave excitation force. Haslum [8] researched on the methods that can be used to estimate the differences in frequency of first and second-order linear waves from SPAR platform motions. The approach that was used is analytical calculations including linear frequency domain, wave frequency model responses, and responses in the mode of heave or pitch motions. For the experiment, the model was only tested in the free decay condition so that values of the heave drag \( (C_{d,z}) \) and pitch drag \( (C_{d,p}) \) are obtained.

Djatmiko et al. [9] has reported a study by conducting a mini SPAR physical model fabrication followed with experimental and numerical analysis on the motions and dynamic mooring tension under variations in wave headings. The study shows the direction of the wave affects motion and tension of mooring system variably. Then Gumelar [10] has modeled SPAR with helical strakes on the mooring system with to be investigated based on experimental and numerical methods. Fairlead height variations are the difference in the study with the results that helical strakes can reduce the maximum value of the heave and pitch motions.

From several literature study above, it can be seen that there are still not many studies that assess the effects of the presence of the heave plate on SPAR and its effect on damping and added mass. This reason has motivate the current experimental study on heave damping due to heave plate additions at SPAR keel. This experimental study is conducted at the Indonesian Hydrodynamics Laboratory, Surabaya, and commenced with the calculation of the parameters that needed to carry out experiment such as heave plate configuration and sizing, radius of gyration, mooring stiffness, and stability of the SPAR model. After conducting the experiment and finding out the results, the analytical and strip theory computations are carried out to derive data to be compared with the experiment results.

2. Methodology

2.1 Experiment and Analytical Computation Procedures

The primary work in the current study is experimental on SPAR physical model, and supported by analytical and theoretical works. The experimental works were conducted at the Indonesian Hydrodynamics Laboratory (IHL), Surabaya. The analytical and theoretical computations, comparative evaluation and analysis were carried out at the Department of Ocean Engineering, Institut Teknologi Sepuluh Nopember, Surabaya. The arrangement and procedures of the study may be listed as in the following:

- Study literature based on laboratory data and structural models used.
- Designing the SPAR model, heave plate, and mooring lines.
- Perform calibration of model, includes mass distribution, mooring stiffness, vertical center of gravity, and the radius of gyration.
- Prepare and calibrate instrument and equipment such as Qualisys Motion Capture Camera.
- Running experiment, in particular free decay test.
- Processing the experimental data with MATLAB program to get damping and natural period values.
- Performing analytical computations to obtain heave damping and heave added mass values.
- Performing the strip theory computations utilizing the MATLAB program to derive the heave decay graph.
- Comparative analysis of experimental results with the results from analytical and strip theory computations.

2.2 Structure Modelling

Parametric evaluation has been performed to derive the SPAR model configuration and sizing. Reference is made on a full-size SPAR with displacement of some 32,000 tons, and the model is taken at a scale of 1: 125 to the full size. The results of the structure dimension analysis for the experiment and the related scaling factors can be seen in Table 1. These dimensions include SPAR size, heave plate, total mass, mooring stiffness, KG and radius of gyration. The SPAR model with the heave plate that has been revitalized as shown in Figure 1. The SPAR model is made of PVC pipe, the heave plate is made of acrylic, the topside is made of plywood and inside the SPAR body there is a ballast consisting of a height-adjustable screw thread to achieve equilibrium.

| Parameter                   | Unit | Model Size | Scale Factor | Full Scale Size |
|-----------------------------|------|------------|--------------|-----------------|
| SPAR Diameter               | m    | 0.14       | \(\lambda\)  | 17.5            |
| Heave Plate Diameter        | m    | 0.182      | \(\lambda\)  | 22.75           |
| Heave Plate Thickness       | m    | 0.005      | \(\lambda\)  | 0.625           |
| SPAR Height                 | m    | 1.234      | \(\lambda\)  | 154.25          |
| Fairlead Height             | m    | 1.170      | \(\lambda\)  | 146.25          |
| Free Floating Draught       | m    | 1.034      | \(\lambda\)  | 129.25          |
| Moored Draught              | m    | 1.114      | \(\lambda\)  | 139.25          |
| Vertical CoG (KG)           | m    | 0.457      | \(\lambda\)  | 57.125          |
| Radius of Gyration abt x-axis (Rxx) | m   | 0.55       | \(\lambda\)  | 68.75           |
| Radius of Gyration abt y-axis (Ryy) | m   | 0.55       | \(\lambda\)  | 68.75           |
| Total Mass                  | kg   | 16.503     | \(\lambda^3\) | 32,232,422      |
| Mooring Stiffness           | kN/m | 328.5      | \(\lambda^3\epsilon\) | 5,261 |

Table 1. Data and properties of the SPAR

![Figure 1. Model of the SPAR with ballast configuration](image-url)
The ballast consists of six (6) iron plates and two (2) blocks. Any one (1) block consists of four (4) iron plates arranged in the keel part of SPAR model. The other block is located 91.5 cm above the keel consisting of two (2) iron plates as depicted in Figure 1.

2.3 Free Decay Test
The experimental works were conducted at the IHL, especially in its Maneuvering & Offshore Basin (MOB) sized 60.0 m × 35.0 m × 2.5 m (L x B x d), equipped with segmental random wave generator. SPAR and the mooring lines are arranged in a test tank to adjust the conditions of the tank.

Figure 2. Experimental arrangement of SPAR model at the IHL – MOB
(a) side view, (b) top view

The SPAR model arrangement at MOB, including the instruments and devices can be seen in Figure 2. The experiment on SPAR model was carried out for two (2) type of tests:
- Free decay test on SPAR model without heave plate,
- Free decay test on SPAR model with heave plate.

Figure 3. Underwater view of moored SPAR model

During experiment on heave decay test, the coordinates of the passive markers on the model are recorded by Qualisys and the results are then be plotted into the heave decay graph. The test was carried out by oscillating in the direction of the heave mode that is on the negative (-) z-axis with an initial amplitude of 1.0 cm. Figure 3 shows the photo of SPAR model moored underwater. Testing was done
for each decay test. If the test result is not appropriate, the test should be repeated until satisfactory result is attained.

2.4 Processing Experiment Data

The results of the heave decay test after it is processed by accounting for the calibration factor is as presented in Figure 4. This figure indicates the SPAR model with heave plate has a higher amplitude in the first cycle in comparison to the model without heave plate. But for the second and further cycles, the amplitudes of model with heave plate are smaller. This means the damping of the heave plate is effective. In addition, the period of the model with heave plate eventually are becoming longer. Using the help of MATLAB software, the values of the elevation peaks or amplitudes and the periods of the decay curves are read and accumulated, and ready to be analyzed further.

![Figure 4. Experiment free decay test result (full scale)](image)

The average period obtained from the aforementioned analysis of decay elevation gives the the natural period of the heave motion, $T_{nz}$. After knowing the natural period, $T_{nz}$, the heave added mass, $A_{33}$ can be found by applying equation (1) [11]:

$$A_{33} = \frac{T_{nz}^2}{4\pi^2} . C_{33} - M$$

(1)

With $M$ is the structure mass and $C_{33}$ is the stiffness coefficient whose value is obtained from analytical calculations. Next to the damping ratio value, $b_f$ can be determined by knowing the logarithmic decrement, $\delta$ like equation (2) [5]:

$$\delta = \frac{1}{N} \ln \left( \frac{\phi_N}{\phi_0} \right)$$

(2)

Where $N$ is the number of cycles and $\phi_N$ is the peak amplitude of the $N$-oscillation. Then the damping ratio or damping factor value, $b_f$ can be determined by equation (3):

$$b_f = \frac{1}{\sqrt{1+(\frac{2\pi}{\delta})^2}}$$

(3)

So the heave damping, $B_{33}$ can be determined by equation (4):

$$B_{33} = 2\zeta_3 \sqrt{(A_{33} + M)C_{33}}$$

(4)

The results hydrodynamic properties obtained from processing the experimental data on decay test are shown in Table 2.
The values of the damping factor and natural frequency are known in Table 2. From the table above, it can be seen that the heave damping increase that occurs due to the heave plate, has a value below 1.0 ($b_f < 1.0$), which means that the systems are underdamped. Next, the damping analysis is continued by exploring the linear and quadratic damping factors. In conjunction to this the following equation (5) is applied [12]:

$$A_{33} \ddot{\zeta} + B_{33}^{(1)} \dot{\zeta} + B_{33}^{(2)} \zeta + C_{33} \zeta = 0$$  \hspace{1cm} (5)

Where $B_{33}^{(1)}$ is the linear damping and $B_{33}^{(2)}$ is the quadratic damping. The values of both damping are obtained from PQ graph, so that if the values of $p$ and $q$ have been found, the linear and quadratic damping can be determined by equations (6) and (7):

$$B_{33}^{(1)} = \frac{2 p A_{33}}{r_{\text{nz}}}$$  \hspace{1cm} (6)

$$B_{33}^{(2)} = \frac{3}{8} q A_{33}$$  \hspace{1cm} (7)

The PQ graph is obtained with the help of the MATLAB program from processing experiment data. From this the linear and quadratic damping values of SPAR with and without heave plate can be seen in Table 3.

| Parameter                | SPAR | SPAR + Heave plate | Difference |
|--------------------------|------|--------------------|------------|
| Natural Period (s)       | 15.84| 16.27              | 3 %        |
| Added Mass (ton)         | 1.488| 2.536              | 77 %       |
| Damping Ratio (%)        | 2.92 | 4.28               | 47 %       |
| Heave Damping [kN/(m/s)] | 772.66| 1,148.15          | 49 %       |

From the table above, it can be seen that the heave damping increase that occurs due to additional of the heave plate on the SPAR keel is dominated by the increase in linear damping, reaches 115%.

3. Results and Discussions

3.1 Responses

Assuming that the SPAR structure is subject to wave excitation, one could then identify the energy response that is generated by the structure due to external harmonic forces. The damping response curve is resulted from the relation between the non-dimensional magnification factor $\xi_{20}/\xi_{zz}$, where $\xi_{20}$ is the heave amplitude and $\xi_{zz}$ is the static heave deflection, and the frequency ratio $\omega/\omega_{nz}$, where $\omega$ is the frequency of excitation and $\omega_{nz}$ is the heave natural frequency. Those two ratios are then governing the damping factor or damping ratio $b_f$. The magnification factor can be determined by equation (8) [13,14]:

$$\frac{\xi_{20}}{\xi_{zz}} = \frac{1}{\sqrt{[1-(\omega/\omega_{nz})]^2 + [2b_f(\omega/\omega_{nz})]^2}}$$  \hspace{1cm} (8)

The values of the damping factor and natural frequency are known in Table 2. The excitation frequency was varied from 0.0 up to 1.6 rad/s. The results of the damping response curves or
magnification factor curves for SPAR model with and without the heave plate can be seen in Figure 5. From the graph, it can be found the maximum response and area under the curve as listed in Table 4. These actually indicate how much heave damping energy generation is reduced when the heave plate is attached to the model.

![Figure 5. Damping response curves](image)

**Table 4. Results of damping response analysis**

|                      | SPAR     | SPAR + Heave Plate | Difference |
|----------------------|----------|--------------------|------------|
| Maximum Response     | 16.33 m/m| 10.57 m/m          | -54 %      |
| Response Area        | 6.51 m²  | 5.1 m²             | -30 %      |

Next, it was also important to analyze the heave phase angle $\varepsilon_z$ of the damping response that occurs. The response phase angle is the rotation angle difference between the peak of the wave and the peak of the successive motion. This can also be measured as the time elapsed between the peak of the wave and the peak of the successive motion divided by the period of movement and multiplied by one cycle motion elevation or $2\pi$ rad [13]. The phase angle value is obtained from equation (9).

$$\tan \varepsilon_z = \frac{2b f(\omega / \omega_n)}{1 - (\omega / \omega_n)^2}$$

(9)

![Figure 6. Damping response phase angle curves](image)
Results of the response phase angle curves is plotted as in Figure 6. From the graphs in Figure 6, it can be seen that the heave plate addition to SPAR does not necessarily make the phase angle curve more sloping. Although it can enlarge the damping factor $b_f$ value and reduce the response that occurs, it does not make the curve sloping significantly. This is because the $b_f$ value that is generated from the experiment was very small ($b_f < 0.05$). Therefore, it can be seen that the change in the response phase angle that appears initially with very low slope then when approaching the frequency ratio of 1.0, the phase angle increase drastically, then slow down again when $\omega/\omega_{nz}$ is increasing. Because the phase angle changing do not coincide with the frequency ratio of 1.0, it can be concluded that the possibility of the SPAR structure experiencing resonance will be relatively small either with or without the heave plate addition.

3.2 Reaction Force

As a result of the oscillations during experiment, the SPAR structure experiences the reaction force as a result of the added mass change (inertial force), damping force, and stiffness force, as shown in equation (10):

$$F_{33} = A_{33} \ddot{\eta} + B_{33} \dot{\eta}_3 + C_{33} \eta_3 \tag{10}$$

From the decay test data, the changing of reaction force with the elapsed time due to the oscillation of wave excitation can be analyzed. The results of heave reaction forces for SPAR with and without heave plate in time series plot are exhibited in Figures 7 and 8. By observing the two graphs in Figures 7 and 8, it can be seen that the heave plate addition to the SPAR can also reduce the heave reaction force. The graphs are further processed to yield some stochastic parameters of the reaction force, to find out the reduction in heave reaction force that occur as shown in Table 5.

![Figure 7](image7.png)

**Figure 7.** Heave reaction force on SPAR without heave plate

![Figure 8](image8.png)

**Figure 8.** Heave reaction force on SPAR with heave plate
Table 5. Stochastic values of heave reaction force

| Reaction Force (kN) | SPAR | SPAR + Heave Plate | Difference |
|---------------------|------|--------------------|------------|
| $F_{\text{rms}}$    | 1344 | 875                | -35 %      |
| $F_{\text{avg}}$    | 1218 | 904                | -26 %      |
| $F_{\text{sig}}$    | 1379 | 1024               | -26 %      |
| $F_{\text{max}}$    | 4064 | 3599               | -11 %      |
| $F_{1/10}$          | 1761 | 1307               | -26 %      |
| $F_{\text{ext}}$    | 3992 | 2910               | -27 %      |

3.3 Analysis by the Analytical Method

Firstly, by the analytical method the heave added masses for bare cylinder and cylinder with plate on the keel are estimated by equation (11) [15]:

$$A_{33} = 2.09 \rho r^3$$  \hspace{1cm} (11)

Further, the heave added masses for bare cylinder and cylinder heave plate can be determined theoretically by equation (12) and (13):

$$m_a = A_{33} = \frac{1}{12} \rho \left[2D_d^3 + 3\pi D_d^2 z - \pi^3 z^3 - 3\pi D_s^2 z\right]$$ \hspace{1cm} (12)

where,

$$z = \frac{1}{\pi} \sqrt{D_d^2 - D_s^2}$$  \hspace{1cm} (13)

$D_s$ is SPAR diameter and $D_d$ is heave plate diameter. Then added mass coefficient $C_a$ is calculated by equation (14):

$$C_a = \frac{A_{33}}{M + A_{33}}$$  \hspace{1cm} (14)

Then the free floating heave natural period can be determined using equation (15) below:

$$T_{nz} = 2\pi \sqrt{\frac{h(1+C_a)}{g}}$$  \hspace{1cm} (15)

For the damping ratio, the obtained value is the result of a calculation from Equation (16) [10].

$$b_f = \frac{F_3(t) - (M + A_{33})\dot{\zeta} - C_{33} \zeta}{2\zeta_3 \sqrt{(A_{33} + M) + C_{33}}}$$  \hspace{1cm} (16)

Here $F_3$ is the heave excitation force and $\zeta_3$ is the acceleration of the structure motion. Comparison of the experimental and analytical results will be presented together with the results of strip theory in Table 6 to be shown in the next sub-section.

3.4 Strip Theory Analysis

Heave decay graph is obtained from the Strip Theory Program "SEAWAY for Windows" [16] which was run with the aid of MATLAB software. In the manual book, it is explained that the decay graph is obtained from Equation (17):

$$\zeta = \zeta_a \cdot e^{-\nu \cdot t} \cdot \left\{\cos(\omega_0 \cdot t) + \frac{\nu}{\omega_0} \cdot \sin(\omega_0 \cdot t)\right\}$$  \hspace{1cm} (17)

With $\zeta_a$ is the given initial amplitude (m), and $\omega_0$ is the natural frequency of the structure (rad/s). Whereas $\nu$ is the result of the damping and moment of inertia that is defined in equation (18):

$$2\nu = \frac{B_{33} + B_{32p}}{I_{xx} + A_{33}}$$  \hspace{1cm} (18)
Considering equation (17), the natural frequency accounted for is the result of the experiment. The given initial amplitude is equated with the value taken for the experiment, which is 1.0 cm on the model scale or 1.25 m if it is used for the case of the full scale. The values of parameter \( v \) are derived from time-domain simulation. Thus the results could also be presented in the decay graphs that are simulated replicate the experimental results. These will lead to the derivation of natural period and the damping ratio that are expected to approach the experimental results. The decay graphs from experiment and strip theory are plotted together in Figure 9.

![Decay graphs comparison](image)

**Figure 9.** Comparison of decay graphs from experiment and strip theory
(a) SPAR model without heave plate; (b) SPAR model with heave plate

| Parameter          | Condition          | Experiment | Analytical | Strip Theory | Difference Experiment & Analytical | Difference Experiment & Strip Theory |
|--------------------|--------------------|------------|------------|--------------|-------------------------------------|--------------------------------------|
| Heave Natural Period (s) | SPAR               | 15.840     | -          | 15.844       | -                                   | 0.03%                               |
|                    | SPAR + Heave Plate | 16.270     | -          | 16.279       | -                                   | 0.05%                               |
| Heave Added Mass (ton) | SPAR               | 1,488.5    | 1,435.1    | 1,446.6      | 3.58%                              | 2.81%                               |
|                    | SPAR + Heave Plate | 2,535.7    | 2,536.2    | 2,572.3      | 0.02%                              | 1.45%                               |
| Heave Damping Ratio (%) | SPAR               | 2.915      | 2.915      | 2.910        | 0.01%                              | 0.17%                               |
|                    | SPAR + Heave Plate | 4.276      | 4.441      | 4.280        | 3.86%                              | 0.10%                               |
| Heave Damping [kN/(m/s)] | SPAR               | 772.7      | 771.4      | 770.7        | 0.17%                              | 0.26%                               |
|                    | SPAR + Heave Plate | 1,148.2    | 1,192.5    | 1,149.9      | 3.86%                              | 0.16%                               |

From graphs in Figure 9 it can be observed that the decay curves of the SPAR without heave plate from the strip theory agree well with the experiment. Observing the SPAR with heave plate, in the first cycle the amplitude difference is visible approximately 53%, however for the rest of the cycles the difference may be considered insignificant. This is similar to the findings as reported in [17,18].

Comparison of results from experiment, analytical method, and strip theory is summarized in Table 6. For the case of natural periods, SPAR without and with heave plate show infinitesimal differences with the strip theory, only some 0.03% and 0.05%, respectively. Concerning the heave added mass, experiment SPAR without heave plate differs, respectively, 3.58% and 2.81%, with analytical method...
and strip theory. Interestingly, the differences of experimental result for SPAR with heave plate are even lower, namely only 0.02% with result of analytical method and 1.45% with result of strip theory [17].

5. Conclusions
Experimental study of heave damping due to the heave plate addition on the SPAR keel, followed by the analysis by implementing analytical method and strip theory could be concluded, as follows:

1. Analysis of data from the experiment by way of the free decay test shows the heave plate on the SPAR keel sized 1.3 x the hull diameter could be expected to increase the heave damping as much as 49%.
   - The heave damping increase for SPAR with heave plate is indicated by the reduction of the amplitudes of each successive cycle in comparison with that without heave plate.
   - The increase in the heave damping value is dominantly affected by linear heave damping. Which in turn affect the reduction in the reaction force and the responses experienced by the SPAR. From the analysis, it is known that heave plate addition on the SPAR keel may reduce the reaction force and the response in the order of 35% and 54%, respectively.

2. Comparisons of results from experiment, analytical method and strip theory show fairly good agreement with specific findings:
   - For the case of heave damping ratio on SPAR without heave plate, the difference between results from experiment and analytical as well as the strip theory are, correspondingly, 0.01% and 0.17%. For the case of SPAR with heave plate, the difference between experiment and analytical method increases to 3.86%, but the difference between experiment and strip theory reduces to only 0.10%.
   - For the case of heave damping value on SPAR without heave plate, the difference between results from experiment and analytical as well as the strip theory are, correspondingly, 0.17% and 0.26%. For the case of SPAR with heave plate, the difference between experiment and analytical method increases to 3.86%, but the difference between experiment and strip theory reduces to only 0.16%.

3. Overall, results of the experimental study could be considered satisfactory as demonstrated by the effectiveness the heave plate to reduce the SPAR heave response brought about the increase in hydrodynamic damping. This finding especially is verified by results from analytical method and strip theory.

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