Experimental Study of the Effect of Waves on SPAR Responses with and without Heave Plate in Intact and Damaged Mooring Systems

Murdjito[1], Gilrandi Adi Negoro[1], Eko Budi Djatmiko[1] and Baharuddin Ali[2]
[1]*Department of Ocean Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia*
[2]*Balai Teknologi Hidrodinamika (BTH) – BPPT, Surabaya, Indonesia*

Keywords: SPAR, Heave Plate, Irregular Waves, Dynamic Responses.

Abstract: This research discusses the effects of heave plate utilization against dynamic responses of SPAR due to random waves. The analysis has been done by numerical and experimental methods. The experimental method was held in Maneuvering Ocean Engineering Basin of Balai Teknologi Hidrodinamika (BTH) – BPPT. The model scale of SPAR was constructed based on the classic SPAR prototype with taut mooring systems using four identical moorings in a 1:125 scale factor. Both experimental and numerical studies were conducted in time domain analysis with heave plate utilization in the keel of SPAR as the main variable. The diameter of the heave plate has a 1.5 ratio to the outer diameter of SPAR. Each analysis was conducted in intact and damaged mooring systems. The analyzed variables of dynamic responses are the surge, heave, pitch, and maximum offset of the SPAR. Results of both the experimental and numerical studies were then be compared, showing that the heave plate does not affect surge and pitch responses significantly. On the other hand, it significantly and consistently reduces the SPAR heave responses in every condition of analysis in both the numerical and experimental methods. The most significant reduction of SPAR heave response occurred when the mooring systems were in damaged condition, i.e., 33.29% and 27.84% heave reduction in the experimental and numerical method, respectively. The study also shows that the heave plate reduces SPAR maximum offset up to 31.69% in experimental analysis and 11.22% in numerical analysis.

1 INTRODUCTION

The necessity of hydrocarbon fuel which keep growing each year, demands hydrocarbon exploration in deep water to fulfil the hydrocarbon shortage. Therefore, the needs of structural and technology advancement for deep-water exploration cannot be neglected any further (Soeb et al, 2017). Between all development in deep-water exploration technology, SPAR floating platform has been the most optimal, efficient, and economic solution to be used as deep-water drilling and production facility (Glanville et al, 1991) (Horton and Halkyard, 1992).

SPAR floating platform has also been developed even further as a floater of floating offshore wind turbine (FOWT), which economically efficient choice in water depth above 50 meters (Jonkman and Matha, 2011).

The motion responses of SPAR is relatively low due to its very deep draught. This advantage, enhances the security of rigid risers below SPAR in deep-water production facility (Tao, Lim and Thiagarajan, 2004). SPAR is also easier to be moved to another location, and also does not affected by water depth or earthquake (Soeb et al, 2017). Some of SPAR excellences are:

- Can be operated in deep-water up to 3000 m water depth, as drilling or production facility.
- It has absolute stability because of its center of buoyancy, which always above the center of gravity.
- Can be utilized as mobile drilling rig.
- It has better sea keeping characteristics compared to the other mobile drilling unit.
- Simplify the installation and operation of mooring and cable systems.
- Risers or other drilling units are protected inside its hull.

These advantages, makes SPAR more likely to be chose and more superior than the other alternative in utilization as drilling or production facility in deep-water (Jain and Agarwal, 2003).

The cylindrical hull of SPAR, which has a massive draft, provides wave load reduction to the

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SPAR system due to its massive displacement which produces damping effect (Jain and Agarwal, 2003). SPAR also requires mooring systems to ensure its position still and stable (station – keeping). The dynamic responses of SPAR significantly affects the mooring lines tension. Yet, the type and characteristics of the mooring systems also govern the dynamic responses of SPAR (Seebai and Sundaravadivelu, 2009). Between all of dynamic loads experienced by SPAR, wave load has the most impact to SPAR dynamic responses. It is because the more closer the natural period of the structure to the wave period, the bigger dynamic responses produced (Djatmiko, 2012). Therefore, it is important to inspect the correlation of natural period of the structure and its environment in design consideration.

A collision between dynamic loads of waves and SPAR will produces dynamic responses in six degree of freedom. Those are surge, sway, heave, roll, pitch, and yaw. These dynamic responses, which hazardous to risers integrity, need to be minimalized (Tao, Lim and Thiagarajan, 2004). Heave response also has been found harmful in small SPAR platform (Fischer and Gopalkhrisnan, 1998). Some solutions to reduce the heave responses of SPAR has been offered by previous studies, which are: increase the damping of the system, dissociate the natural period of the structure further from the wave period, and reduce the wave excitation forces acting on the structure (Haslum and Faltinsen, 1999). The utilization of heave plate at the SPAR keel will provide a significant increase in the damping of the system, which will also reduce the heave response of the structure (Tao, Lim and Thiagarajan, 2004). Further research results shows that the diameter of the heave plate, affects the increase of added mass, which will affects the damping of the system and the motion responses of the structure (Sudhakar and Nallayarasu, 2014). The utilization of double heave plates in the keel and the hull of classic SPAR also significantly affects the heave response of the SPAR. The diameter of the heave plates, and the distance between the heave plates, are the main variable, which contributes to the change in SPAR viscous damping (Subbulakshmi et al, 2015).

This research, discusses about the effects of the heave plate utilization in the keel of SPAR to its dynamic responses against irregular waves in intact and damaged mooring systems. The research has been done in numerical and experimental method, using classic SPAR model, which has been studied by Ivandito Herdayanditya in his research and has 1:125 scale factor, with heave plate utilization as the main modification. The numerical study has been done using Orcaflex 9.2a, and the experimental study was held in Maneuvering and Ocean Engineering Basin (MOB) of Balai Teknologi Hidrodinamika (BTH) – Badan Pengkajian dan Penerapan Teknologi (BPPT).

2 LITERATURE REVIEW

The research about non-linear response of SPAR platform due to wave, and current load in ultra-deep water and how water depth affects its responses has been studied in detail (Soeb et al, 2017). Chitrapu, et al. had also researched about non-linear responses of SPAR in varies of environment using time domain simulation (Chitrapu, Saha and Salpekar, 1998). Jain and Agarwal also accomplished a dynamic analysis of SPAR using time domain simulation, which concludes that the responses of SPAR due to waves and currents need to be restricted, since SPAR platform usually used as production and drilling facility (Jain and Agarwal, 2003). Tao, et al. also studied the correlation between heave response in classic SPAR and its viscous damping (Tao, Lim and Thiagarajan, 2004). Fischer and Gopalkrishman numerically and experimentally analyzed the characteristics of SPAR heave response, and represented the importance of heave response consideration in SPAR (Fischer and Gopalkhrisnan, 1998). Halsum and Faltinsen offered some solutions to reduce the heave responses of SPAR (Haslum and Faltinsen, 1999), which are:

- Increase the total damping of the system.
- Dissociate the natural period of the structure further from the wave period.
- And significantly reduce the wave load excitation forces.

Tao, et al. research, shows that the heave response of SPAR platform may be reduced by heave plate utilization around its hull, which will dramatically increase the damping of the structure (Tao, Lim and Thiagarajan, 2004). Yet, Halsum and Faltinsen mentioned that after using heave plate, the heave response of SPAR still in a critical state (Haslum and Faltinsen, 1999). Aside from heave plate utilization, an additional damping system of a SPAR may be achieved by installing helical strakes around its hull or increasing its draught. Sudhakar and Nallayarasu studied even further about the effects of heave plate utilization and its diameter to the SPAR responses, and found the optimal heave-plate diameter ratio to SPAR diameter (Sudhakar and Nallayarasu, 2014). Subbulakshmi, et al. also studied the effects of double heave plates utilization to the heave response reduction of SPAR, and found the optimal diameter ratio of the heave plates and the optimal distance between them to reduce the heave response (Subbulakshmi et al, 2015).

3 OBJECTIVES AND SCOPE OF STUDY

The objective of this research is to comprehend how far the heave plate utilization in the SPAR keel affects the stochastic parameter of its dynamic responses. The dynamic responses which to be analysed are surge, heave, pitch, and maximum offset. The scope of study and boundaries of this research are as follows.

- Experimental and numerical study only considered one wave characteristic with 0º wave heading.
- The type of mooring systems is taut mooring system, with four identical mooring lines.
- The experimental and numerical study was conducted in the condition of intact and damaged mooring system.
- The influence of low frequency wave was not included in the consideration of the analysis.
- The only mooring line tension considered in this study is the pre-tension of mooring lines, which is similar for each mooring lines.
- Numerical study was conducted in Orcaflex 9.2a as a comparison of the experimental study.

4 METHODOLOGY

The flow and procedure of this research was conducted in stages as follows.

- The literature reviews was performed by referring to the previous study. The data collection of the laboratory, scale model, and any other experimental and numerical aspects was also conducted in this step.
- The determination of design criteria like scale factor, acceptance criteria, and so on.
- Modeling of the scale model, which comprised: the design aspects of the scale model, instrument preparation, trials, processing and analyzing the experimental data result.
- Numerical modeling of the structure, which consists: modeling stage in the software, numerical model validation, and numerical trials.
- Analyzing and comparing the results of the experimental and numerical study followed by conclusions.

Figure 1: Scale model the SPAR with heave plate.

5 RESULTS AND DISCUSSION

5.1 Experimental Modeling

The experimental modeling consists two main section, which are scale model modeling, and mooring system modeling. The scale model of the SPAR hull was made of PVC pipe with 14 cm diameter. The heave plate was made of acrylic, while the topside was made of plywood as can be seen in Figure 1. The ballasting system of the SPAR was installed inside of the hull, which was made of six cylindrical steel with a shaft in the middle piercing each cylindrical steel. These cylindrical steel's position can be optimized inside the hull to achieve the desired stability equilibrium in water, its weight distribution parameter like keel to gravity (KG) and radius of gyration was obtained by a series of calibration. The ballasting system of the scale model was divided into two blocks of cylindrical steel. The first block consists four cylindrical steel which located in the keel of the SPAR, and the other blocks consists two cylindrical steel which located at 91.5 cm above the keel. The mooring system model was made of two section. The first section was rubber, and the second section was steel wire sling. The stiffness of the mooring lines, which need to be considered, was obtained by a series of calibration and calculation using Hooke's law equation. The data results from experimental modeling can be seen at table 1. The mooring system of the SPAR model was installed in a configuration like Figure 2, 5.5, and 5.6. While the ballast of the SPAR and its configuration can be seen in figure 5.1.

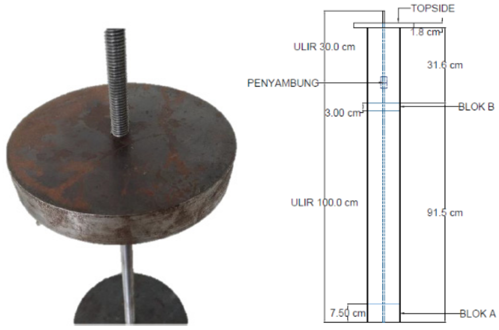

Figure 2: Cylindrical steel as ballast (left) and its configuration inside the SPAR hull (right).

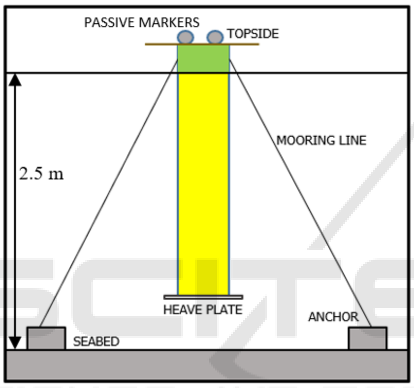

Figure 3: Side view of mooring system configuration.

Table 1: SPAR data and properties.

SPAR PROPERTIES (SCALE 1:125)			
Parameters	Scale Model Dim.	Scale Factor	Full Scale Dim.
Hull diameter (m)	0.140	λ	17.500
Keel diameter (m)	0.150	λ	18.750
Draft without heave plate (m) – Free floating	1.029	λ	128.681
Draft without heave plate (m) – Moored	1.111	λ	138.896
Draft with heave plate (m) – Free floating	1.034	λ	129.305
Draft with heave plate (m) – Moored	1.116	λ	139.520
Hull height (m)	1.245	λ	155.625
Keel cylinder height (m)	0.053	λ	6.625
Fairlead height of SPAR without from keel (m)	1.165	λ	145.625
Fairlead height with heave plate from keel (m)	1.170	λ	146.250
Mass of SPAR without heave plate (ton)	0.016	λ^3	31949.219
Mass of SPAR with heave plate (ton)	0.017	λ^3	32295.918
Keel to Gravity of SPAR without heave plate, KG (m)	0.457	λ	57.125
Keel to Gravity of SPAR with heave plate, KG (m)	0.452	λ	56.508
Roll radius of gyration, Rxx (m)	0.550	λ	68.750
Pitch radius of gyration, Ryy (m)	0.550	λ	68.750
HEAVE PLATE PROPERTIES (SCALE 1:125)			
Parameters	Scale Model Dim.	Scale Factor	Full Scale Dim.
Heave plate diameter (m)	0.210	λ	26.250
Heave plate thickness (m)	0.005	λ	0.625
Mass of heave plate (ton)	0.000 15	λ^3	283.203
SELECTED MOORING LINES PROPERTIES (SCALE 1:125)			
Parameters	Scale Model Dim.	Scale Factor	Full Scale Dim.
Pre-tension (KN)	0.003	$\lambda^3\varepsilon$	6835.771
Rubber			
Axial stiffness, EA (MN)	0.000 0196	$\lambda^3\varepsilon$	39.278
Length (m)	0.2	λ	25.000
Steel wire sling			
Axial stiffness, EA (MN)	0.003 53	$\lambda^3\varepsilon$	7075.487
Length (m)	2.040	λ	255.000

5.2 Numerical Modeling

The numerical model was built based on experimental data structure in full scale. The numerical modeling also consists two main modeling section, which are structural modeling and mooring system modeling. First of all, numerical model of the SPAR was built using 3D diffraction theory in MOSES at its operation draught. The structure was modelled while using heave plate and not. Modeling in MOSES was intended to obtain the hydrodynamic and hydrostatic parameter of SPAR in a particular draught, such as damping matrix, added mass matrix, wave load RAO, and so on. After the validation of the numerical model, the numerical model of SPAR has also been analysed in Orcaflex 9.2a to simulate the random waves while SPAR in moored condition, using the hydrodynamic and hydrostatic data obtained from MOSES as an input in Orcaflex 9.2a. The result of numerical modeling stages can be seen in Figure 4 and Figure 5.

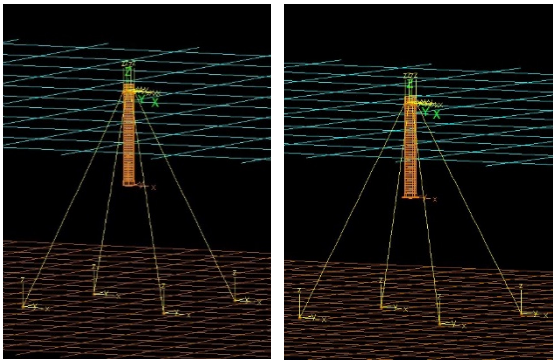

Figure 4: Numerical moored model of SPAR in Orcaflex 9.2a (Full scale) without heave plate (left), and with heave plate (right).

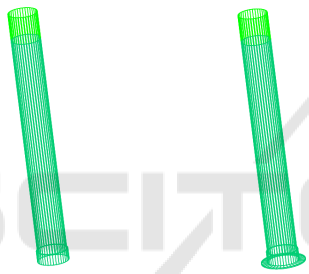

Figure 5: Numerical model of SPAR in MOSES (Full scale) wihout heave plate (left), and with heave plate (right).

5.3 Experimental Analysis

The experimental analysis was conducted in Maneuvering and Ocean Engineering Basin (MOB) of Balai Teknologi Hidrodinamika (BTH) – BPPT. SPAR and its mooring systems was attached together in the MOB based on the planned configuration. The experiment was conducted in four trial conditions, which are:

1. SPAR without heave plate in intact mooring system.
2. SPAR with heave plate in intact mooring system.
3. SPAR without heave plate in damaged mooring systems.
4. SPAR with heave plate in damaged mooring systems.

Each trial was conducted in time domain method with 6 minutes duration, which equivalent as 67 minutes in full scale referring to Froude's model scaling law. Qualysis motion capture camera, which placed under the moving bridge above the MOB, was used to record the translational and rotational responses of SPAR. During the simulation, Qualysis recorded the whole SPAR's movement based on the coordinate of passive marker position shift, which located on the topside of the SPAR. The output from Qualysis was time history responses in six degree of freedom. Whereas the elevation of the trial's waves was measured using wave probe, which placed under the moving bridge, in front of the SPAR. The trial's wave characteristics can be seen in Table 2. The configuration of intact and damaged mooring systems used in the trials can be seen in Figure 6 and Figure 7. While the documentation of the moored model in MOB can be seen in Figure 8.

Table 2: Trial's wave characteristics.

Parameters	Values	Units
Full Scale		
Wave spectrum theory	JONSWAP	-
Hs	6.35	m
Tp	14.5	s
γ	3.3	-
Wave heading	0	Degree
Model (Scale 1:125)		
Wave spectrum theory	JONSWAP	-
Hs	0.0508	m
Tp	1.297	s
γ	3.3	-
Wave heading	0	Degree

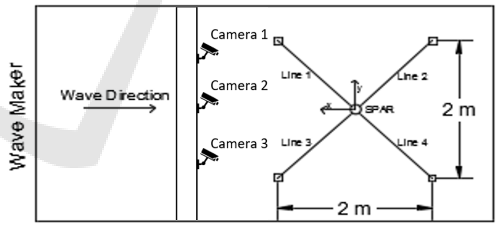

Figure 6: Intact mooring system configuration.

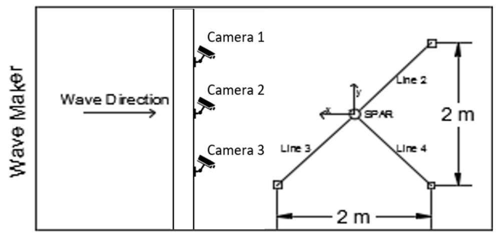

Figure 7: Damaged mooring system configuration.

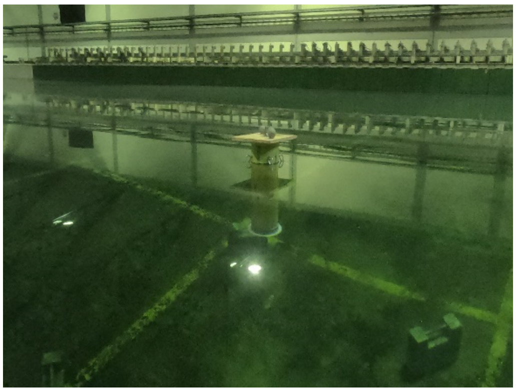

Figure 8: Moored scale model in MOB.

5.4 Numerical Analysis

Firstly, the numerical analysis was conducted in MOSES in frequency domain while SPAR in free-floating state using the operation draught. This analysis was intended to obtain the hydrostatic and hydrodynamic data of SPAR while in operation draught. Then, these data obtained by MOSES such as damping matrix, added mass matrix, and wave load RAO, will be used in Orcaflex 9.2a as an input, then further analyzed in moored condition. All trial set conducted in MOSES can be seen in Table 3.

Table 3: Trial set conducted in MOSES.

Condition	Analysis code	Operation draught
Without *heave plate*	1	*Intact,* 138.896 m
	2	*Damaged,* 136.845 m (based on static analysis in Orcaflex 9.2a)
With *heave plate*	3	*Intact,* 138.896 m
	4	*Damaged,* 137.473 m (based on static analysis in Orcaflex 9.2a)

In Orcaflex 9.2a, analysis was conducted using time domain simulation, in intact and damaged mooring system. Every aspects of simulation such as the duration of the simulation, wave heading, wave characteristics, was based on experimental data in full scale and adjusted as similar as possible. The water depth data in numerical analysis also based on the depth of MOB that scaled into full scale, which is 312.5 meters. The intact and damaged mooring system configuration in Orcaflex 9.2a is the same as experimental configurations.

5.5 Data Results Processing and Discussion

There are several steps conducted to obtain the stochastic parameter of the SPAR responses. The time history responses both from numerical and experimental analysis need to be converted into spectral density response in full scale condition for each dynamic responses. Then further analysis had been done in surge, heave, and pitch responses to obtain their stochastic parameters. Whilst the maximum offset can be obtained directly by plotting the surge and sway responses together, then measure the furthest movement of SPAR during simulation from the initial coordinate. The time history responses obtained from experimental analysis was scaled into full scale using Froude's law. The example of time history responses in full scale can be seen in Figure 9.

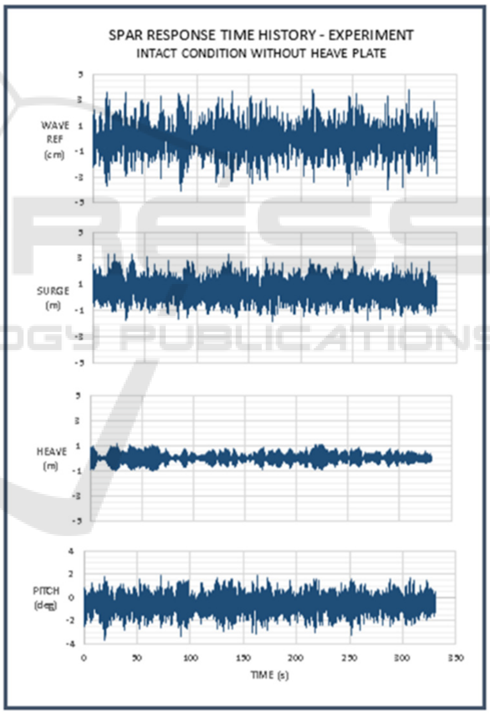

Figure 9: Time history responses output example.

Random waves and responses time history have similar characteristics, so both of them can be processed with the same method. First, the time history data need to be prepared by dividing each wave record into some segment. Every segment has a same point of measurement with the same interval length, which can be the point of zero-up crossing period, zero-down crossing period, or peak period. After that, incremental frequency or usually called

Nyquist frequency can be determined. The Nyquist frequency was used as the interval of the frequency in the converted time history responses, which was converted into a frequency domain record graphic. When the time history data ready, the conversion process was conducted in MATLAB using its Fast Fourier Transform (FFT) feature. The results, which was a record of amplitude of waves or responses in each frequency, further converted into an ordinate of spectral density curve using equation (1) (Djatmiko, 2012). The example of converted time history responses in time domain into frequency domain can be seen in Figure 10. And the example of the conversion results into the spectral density curves can be seen in Figure 11 until Figure 13.

$$S_\zeta(\omega)d\omega = {\zeta_{n0}^2}/{2\delta\omega} \tag{1}$$

Where,

$S_\zeta(\omega)$ = Spectral density ordinate (m^2/(rad/s))

$\delta\omega$ = Nyquist frequency (rad/s)

ζ_{n0} = Wave or responses amplitude (m)

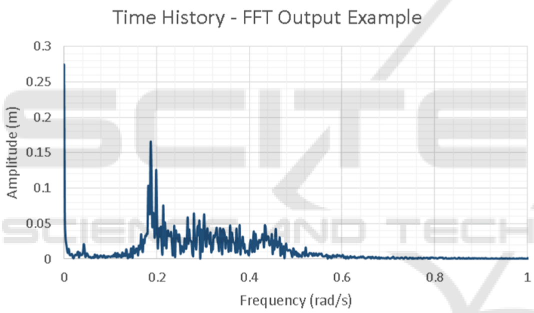

Figure 10: Example of time history FFT output (full scale).

After every component of amplitude in each recorded frequency has been converted into an ordinate of spectral density curve, each set of it was plotted into a diagram with Nyquist frequency as the abscissa. Then, the stochastic value of each diagram can be calculated based on the variants of the wave or responses elevations, which is equivalent with the area under the spectral density curve. The second, and fourth moment of spectral area can also be calculated using equation (2).

$$m_n = \int_0^\infty \omega^n S_\zeta(\omega)d\omega \tag{2}$$

Where m_0 is the variant of wave elevations or response amplitudes. m_1, m_2, and m_4 are the first, second, and fourth moment of spectral area. By knowing the value of these parameters, the stochastic values of each responses can be calculated. In accordance with the scope and boundaries stated before, the contribution of the low frequency components are neglected. Therefore, the stochastic value calculations are started from the wave frequency of 0.26 rad/s, which is the lower limit frequency in wave energy spectrum density.

The stochastic responses calculated in this research are: significant responses, mean of 1/10 highest responses, mean responses, the most probable extreme responses, and the most probable extreme responses with a probability of 99% confidence not exceeded. Those stochastic responses can be calculated using equations as follows.

$$\zeta_{n_s} = 2\sqrt{m_0} \tag{3}$$

$$\zeta_{n_{av}} = {2.5}/{2}\sqrt{m_0} \tag{4}$$

$$\zeta_{n_{1/10}} = {5.08}/{2}\sqrt{m_0} \tag{5}$$

$$\widehat{\zeta} = \sqrt{m_0}\ x\ \sqrt{\left\{2ln\left(\frac{60^2T}{2\pi}\sqrt{\frac{m_2}{m_0}}\right)\right\}} \tag{6}$$

$$\widehat{\zeta_\alpha} = \sqrt{m_0}\ x\ \sqrt{\left\{2ln\left(\frac{60^2T}{2\pi\alpha}\sqrt{\frac{m_2}{m_0}}\right)\right\}} \tag{7}$$

Where,

ζ_{n_s} = Significant responses (m)

$\zeta_{n_{av}}$ = Mean responses (m)

$\zeta_{n_{1/10}}$ = Mean of 1/10 highest responses (m)

$\widehat{\zeta}$ = The most probable extreme responses (m)

$\widehat{\zeta_\alpha}$ = The most probable extreme responses with a probability of 99% confidence not exceeded (m)

T = Duration of waves-making (s)

α = confidence number, 0.01 for 99% confidence not exceeded (m)

According to the results, the response changes between before and after heave plate utilization in each type of stochastic responses are all the same in percentage. Therefore, to simplify the analysis in seeing the changes that occurs, the significant responses was chosen as a representation of the SPAR responses in each motion, which was compared between each condition.

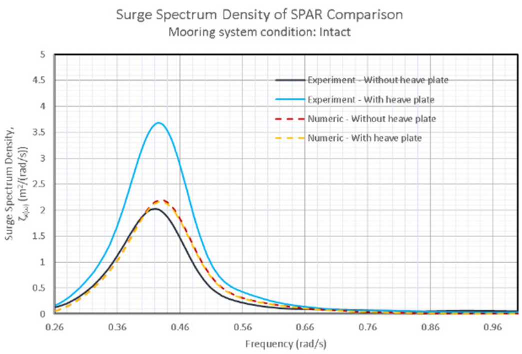

Figure 11: Example of surge responses spectrum density.

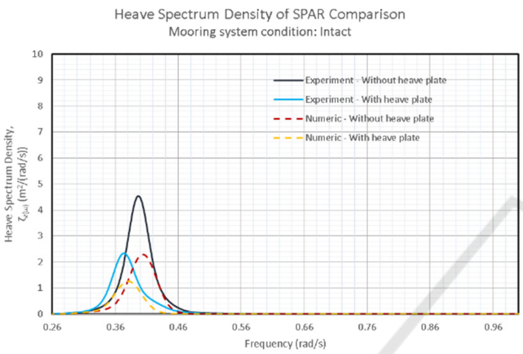

Figure 12: Example of heave responses spectrum density.

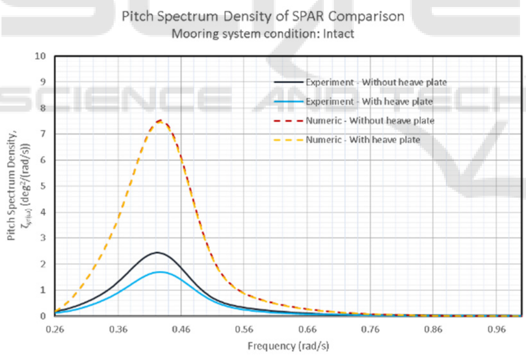

Figure 13: Example of pitch responses spectrum density.

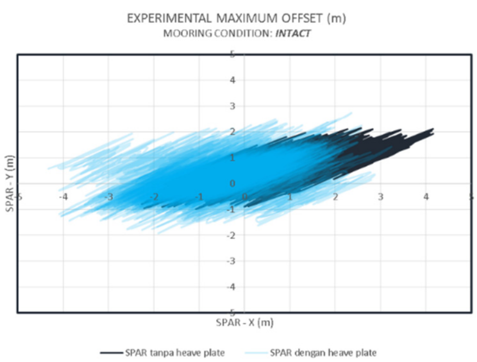

Figure 14: Offset of SPAR graphic example.

All responses assessed from experiment and numeric method was plotted together in both intact and damaged condition to observe the responses reduction due to heave plate utilization more clearly. As discussed above, the area below the spectral density graph is the response's energy which equals to the response's value. Thus, from those comparative graphics, it can be concluded that there are some cases of response amplifications and reductions after heave plate utilizations. All the results are presented in Table 4 to Table 7 below.

5.5.1 Surge Responses

All of the calculation's results of surge significant response's changes in each conditions are presented in Table 4 below.

Table 4: Significant surge of SPAR.

Significant surge responses (m) – Experimental			
Condition	Without heave plate	With heave plate	Reduction
Intact	1.64	1.74	-6.15%
Damaged	1.83	1.82	0.60%
Significant surge responses (m) – Numerical			
Condition	Without heave plate	With heave plate	Reduction
Intact	1.16	1.15	0.84%
Damaged	1.06	1.05	0.86%

5.5.2 Heave Responses

All of the calculation's results of heave significant response's changes in each conditions are presented in Table 5 below.

Table 5: Significant heave of SPAR.

Significant heave responses (m) – Experimental			
Condition	Without heave plate	With heave plate	Reduction
Intact	0.97	0.73	24.16%
Damaged	1.06	0.71	33.29%
Significant heave responses (m) – Numerical			
Condition	Without heave plate	With heave plate	Reduction
Intact	0.73	0.54	26.39%
Damaged	1.12	0.71	27.84%

5.5.3 Pitch Responses

All of the calculation's results of pitch significant response's changes in each conditions are presented in Table 6 below.

Table 6: Significant pitch of SPAR.

Significant pitch responses (m) – Experimental			
Condition	Without heave plate	With heave plate	Reduction
Intact	1.46	1.20	17.65%
Damaged	1.34	1.40	-4.56%
Significant pitch responses (m) – Numerical			
Condition	Without heave plate	With heave plate	Reduction
Intact	2.14	2.13	0.44%
Damaged	2.00	1.99	0.44%

5.5.4 Maximum Offsets

All of the calculation's results of maximum offsets changes in each conditions are presented in Table 7 below.

Table 7: Maximum offsets of SPAR.

Maximum offsets of SPAR (m)			
Intact mooring system			
Method	Without heave plate	With heave plate	Reduction
Experiment	4.65	4.36	6.22%
Numeric	2.46	2.23	9.61%
Damaged mooring system			
Method	Without heave plate	With heave plate	Reduction
Experiment	5.02	3.43	31.69%
Numeric	2.37	2.11	11.22%

As stated before, the maximum offsets value was obtained by plotting the surge and sway responses in each condition during simulation together, then the furthest SPAR movement from the initial condition was calculated as the maximum offset. The plotted graphic example can be seen in Figure 14.

6 CONCLUSIONS

The findings of the study could be revealed as follows:

- Heave plate utilization does not constantly and significantly reduce surge responses. It is indicated by the biggest reduction of surge responses that occurs during simulation was only 0.86%, which happened in numerical analysis. There were some inconsistency happened in experimental method, which the surge responses was amplified by 6.15% in intact mooring system. This inconsistency potentially caused by the couple response between surge and pitch. On the contrary, the heave plate utilization does reduce the heave responses of SPAR, consistently and significantly. It is indicated by the significant reduction that occurs in every condition of experimental and numerical study. The biggest reduction happened in damaged mooring system during experimental study, which was 33.29%. As for pitch, the heave plate utilization numerically does not affects the responses significantly, it is indicated by the reduction are only 0.44% in each condition. Yet, in the experimental study the pitch responses inconsistently changes. Where in intact mooring system it was reduced up to 17.65%, and while in damaged mooring system it was amplified by 4.56%. In some conditions, SPAR model satisfies the requirements of Matthieau instability to occurs, this phenomenon potentially become the cause of the inconsistency in pitch responses.
- Heave plate utilization does reduce SPAR maximum offsets consistently in every conditions. The biggest reduction happened in damaged mooring system of experimental analysis, which was 31.69%.
- The comparison between two methods has found that in surge responses, inconsistency happened while in intact mooring system. In the numerical analysis, the surge responses are slightly reduced, yet in experiment it was amplified. In heave responses the results of the two method shows a convenient agreement, where it has been reduced consistently and significantly in both methods. As for pitch, inconsistency happened while in damaged mooring system, where experimentally it was a bit amplified, but numerically it was slightly reduced.

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