ISSN 1738-3935
New & Renewable Energy 2016. 2 Vol. 12, No. S1 http://dx.doi.org/10.7849/ksnre.2016.02.12.S1.2

[2016-2-WD-001]

Experimental Study on the Suppression of a Vertical Circular Cylinder with a Heave Plate

Lixin Zhu[1] · HeeChang Lim[2]*

Received 31 May 2015 **Revised** 25 January 2016 **Accepted** 25 January 2016

ABSTRACT Studies of floating structures are becoming increasingly important due to their increased application. The hydrodynamic motion response of floating structures must be controlled within a certain range, especially in the resonance region. In this study, a scale model of a circular cylinder having a height of 300 mm, outer diameter 60 mm, natural heave period 0.78 s and a natural pitch period 1.12 s, was designed and analyzed for hydrodynamic load. We compared this model with other models of cylinders with various heave plates systems. In order to find the size effect of the heave plate, two heave plates of 60 and 80 mm in diameter with a thickness of 5 mm. At first, a free decay experiment was carried out to examine the damped heave and pitch period, as well as the hydrodynamic coefficients in the resonance frequency. The motion response was also analyzed to obtain the heave and pitch motion response in a series of regular waves having periods between 0.51 s and 1.24 s. It was observed that the heave plate significantly enhanced the damped heave period, whereas it had a negligible effect on the damped pitch period. Moreover, the peak of heave Response Amplitude Operator (RAO) was observed to be reduced for the heave plate in the resonance region and the peak of heave RAO was shifted to a long period. Furthermore, a comparatively small peak heave RAO was observed in the experiments. It was indicated that pitch motion has an effect on heave motion in the pitch resonance frequency.

Key words Circular cylinder(원기둥), Heave plate(감쇠판), Hydrodynamic motion response(수력학적 운동응답)

Nomenclature

λ : wave length, m
ζ : damping ratio
ω : natural frequency
δ : logarithmic decrement
k : wave number
L : characteristic linear dimension, m
D : cylinder diameter, m
Z : heave motion displacement, m
T : wave period, s
θ : pitch motion angle, rad
A : waterplane area, m^2
V : displaced volume, m^3
m : mass of the whole system, kg
a_{33} : added mass for heave motion, kg
a_{55} : added mass for pitch motion, kgm^2
b : heave motion linearized damping
r_{55} : pitch radius of gyration, m
b^{eq} : pitch motion linearized damping
RAO : response amplitude operator
CG : central of gravity
GM_L : longitudinal metacenter height, m
A_w : amplitude of wave, m

1) Pusan National University
2) Pusan National University E-mail: hclim@pusan.ac.kr
Tel: +82-51-510-2302 Fax: +82-51-512-5236

A_m : amplitude of cylinder motion

C_a : added mass coefficient

1. Introduction

As the energy crisis and sustainable development are becoming the global issues, substantial researches on renewable energies are being widely studied all over the world. Recently, the vast renewable energies collected in the ocean area have been future potential resources. On the other hand, the research regarding floating structures has also been imperative with an increasing trend of installing offshore floating structures. In particular, a spar–buoy platform structure has been considered to be one of the most effective and classical floating structures in deep water. One of recent works, Jonkman[1] presents a complete analysis of static and coupled dynamic analysis of 5 MW spar–buoy wind turbine system. However, the spar–buoy structure generally has a deep draft and large diameter so that the overall system undergoes relatively low heave and pitch motions. In order to achieve this purpose in more efficient way, additional mechanical damping devices or other active damping system would possibly be applied. One of possible methods is to attach a heave plate on the keel region of the spar–buoy platform. Sudhakar & Nallayarasu[2] reported the experimental and numerical results of the hydro–dynamic response of a spar with a heave plate. It has shown that with the increasing of plate diameter, the heave damping increases. The spacing effects on hydrodynamics of heave plates having a cylindrical keel were studied by Tao et al.[3] It was found that the heave plate configuration with a critical spacing depending on Keulegan–Carpenter (KC) number would be mostly beneficial in terms of maximizing damping of the system.

Hydrodynamic coefficients for the spar–buoy structure is the key parameter to be studied. Regarding the work of the added mass and damping coefficients for the different shape plates, Prislin et al.[4] and Molin[5] found a strong relation among various parameters such as hydrodynamic coefficients and the KC number as well as Reynolds number. Phillip et al.[6] studied the effect of the excitation forces on the heave plate attached on the spar hull.

As a fundamental work to understand the role of a heave plate, this study has undertook a spar–buoy model with a heave plate place on regular waves in a wave–flume tank. The spar–buoy model (a cylindrical shape having a length of 300 mm and outer diameter 60 mm) with heave plates (the plates are located at 65 mm apart from the cylinder bottom), which is a scaled model, is precisely designed and manufactured, and has its natural heave period 0.78s. and natural pitch period 1.12s. In the experiment, we expect that the heave plate placed apart from the keel of the spar–buoy model has bigger damping effect and larger added mass. The heave plate models we used in the study are four configurations – the diameters of 60 mm and 80 mm, and thicknesses of 2 mm and 5 mm.

2. Design of Wave Flume Experiment

2.1 Experimental facilities

The experiment was carried out in a laboratory wave flume facility in Kyushu University, Japan. The wave flume having the size of 20 m long, 0.8 m wide, and 1.0 m deep, which has equipped with two vertical motion wave generators in the both ends of the flume as shown in Fig. 1. Two wave generators operated by a computer are mainly used to make a generation of regular waves and at the same time to break up the propagating wave by active absorbing mechanism. Therefore, the designated amplitude and wave period of regular waves could be generated by this active wave control system. In order to make a variety of model experiment, the circular cylinder model is placed in the middle of the wave flume and it is connected with a designated mooring system as shown in Fig. 2.

In order to observe the synchronous wave height, a wave height gauge is installed at 75 cm further upstream of the cylinder model. The measured voltage signals are recorded in a 32 multi-channel data acquisition system (NEC OMNIACE RA2800). In addition, to make an accurate measurement of the movement of cylinder, a high density (HD) video camera was used in the wave flume. The HD camera was set to be the frame resolution of 1,920×1,080 pixel^2, data transfer rate 16,885 kbps, and the frame rate 30 fps (frames per second), etc. In order to find the exact position of floating body from the acquired images, two black points marked at 5 cm vertical distance on the cylinder surface were used as reference points. In order to find the movement of the cylinder, a video camera is located at 3 m apart from the side of wave flume with the aim to record the model movement in 30 fps. After obtaining the video files, based on two black points can be analyzed by using a image processor (Dipp-motion PRO, Kato Koken) so that the heave and pitch motions were acquired.

2.2 Floating Model

In this study, the basic model (model 0) is a single cylinder connected with a ballast bolt. Other various models depending on heave plates are orderly numbered from 1 to 4. The detailed configurations are shown in Tables 1 and 2.

The experimental model is moored at the level of center of gravity (CG) by long taut elastic lines in the both sides of model. The angle between the taut line and free surface is around 6 degs. In the experi-ment, we assume the mooring system has a negligible effect on heave and pitch motion of model.

2.3 Governing equation of motion

In principle, the heave plate could enhance the

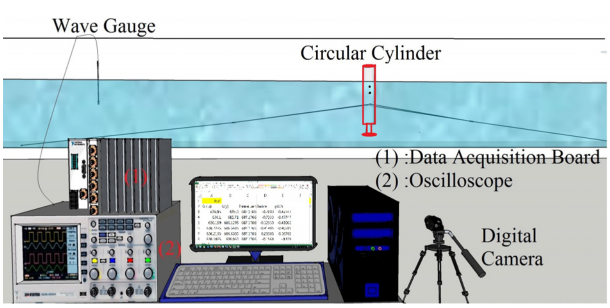

Fig. 1. Schematic diagram of wave flume experiment

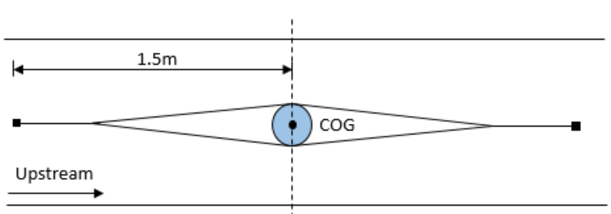

Fig. 2. Schematic diagram for top view of mooring system

Table 1. Properties of a circular cylinder

Specifications	Cylinder
Height (mm)	300
Diameter (mm)	60
Mass (g)	418
Draft (mm)	150
Height of CG	24.5
Resonant Period of Heave/Pitch (s)	0.78/1.12

Table 2. Dimension of heave plates for wave flume experiment

Model No.	Heave Plate	Diameter (mm)	Thickness (mm)
0 (base)	W/O plate	-	-
1	W/ plate	80	5
2		80	2
3		60	2
4		60	5

heave added mass and viscous damping. Based on the dynamics theory, the heave and pitch natural period of a floating cylinder is given as:

$$T_H = 2\pi\left(\frac{M+a_{33}}{\rho g A_w}\right)^{(\frac{1}{2})} \quad (1)$$

$$T_P = 2\pi\left(\frac{Mr_{55}^2 + a_{55}}{\rho g V\overline{GM_L}}\right)^{(\frac{1}{2})} \quad (2)$$

where M, a_{33}, A and $\overline{GM_L}$ are mass and added mass in heave, the area of water plane and longitudinal metacenter height, respectively. In addition, ρ and g are the density of water (the working fluid where the model is submerged) and acceleration of gravity.

The governing equation of heave motion is given as:

$$(m+a_{33})\ddot{Z} + b\dot{Z} + \rho g A_w Z = 0 \quad (3)$$

Equation (3) could be rearranged as an ordinary differential equation as follows:

$$\ddot{Z} + \frac{b}{(m+a_{33})}\dot{Z} + \frac{\rho g A_w}{(m+a_{33})}Z = 0 \quad (4)$$

In Eqn (4), the damping ratio ζ and the natural frequency w are defined as

$$2\zeta\omega = \frac{b}{(m+a_{33})} \quad \text{and} \quad w^2 = \frac{\rho g A_w}{m+a_{33}} \quad (5)$$

For the second order ordinary differential equation, the general solution of Eqn (4) can be written as:

$$Z = z_a \times \exp(-\zeta\omega t) \times (\cos(wt) + \zeta\sin(wt)) \quad (6)$$

Finally, the motion of cylinder could be expressed in Eqn (6) and added mass a_{33} can be obtained through the curve fitting once the motion of cylinder is known.

The added mass coefficient (C_a) is defined and calculated as follows:

$$C_a = \frac{a_{33}}{m+a_{33}} \quad (7)$$

However, when attaching the heave plate on the bottom of the spar, the viscous damping, which is caused by vortex shedding around the plate, becomes to the dominant damping resources. Therefore, the damping ratio could be approximately calculated by

$$\zeta = \frac{1}{\sqrt{1+(\frac{2\pi}{\delta})^2}} \quad (8)$$

where the logarithmic decrement, δ is defined as the natural log of the amplitude of adjacent peak.

$$\delta = \ln\left(\frac{Z_1}{Z_2}\right) \quad (9)$$

3. Results and discussion

3.1 Free decay experiment

The free decay experiment is designed to investigate the damped heave and pitch period of the models, and these values can be used for make a proper wave period for the further detailed experiment. The model is firstly placed in initial vertical displacement and pitch angle for finding the characteristic curve of the heave and pitch free decay experiment, and then the subsequent motions were recorded and stored (see Figs. 3-6).

As shown in figures, the heave and pitch damped period can be calculated by fitting the curves. (i.e., Model 0: 0.78s and 1.12s, Model 1: 0.89s and 1.1s, Model 2 : 0.90s and 1.08s, and Model 4: 0.86s and

1.08s). In Figs. 5 and 6, the heave plate has little effect on the pitch added mass, whereas the heave added mass varies significantly depending on different heave plates (see Figs. 3 and 4). In order to quantify the added mass and damping ratio, the added mass coefficients of natural frequency and damping ratio needs to be estimated and summarized in Table 3.

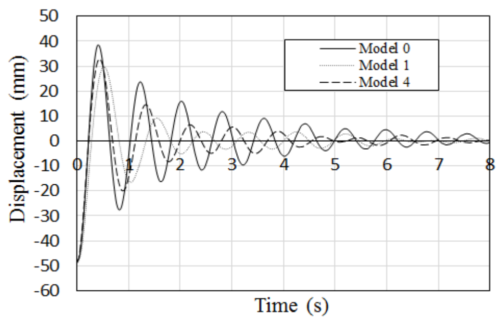

Fig. 3. Heave motion for models with various diameter

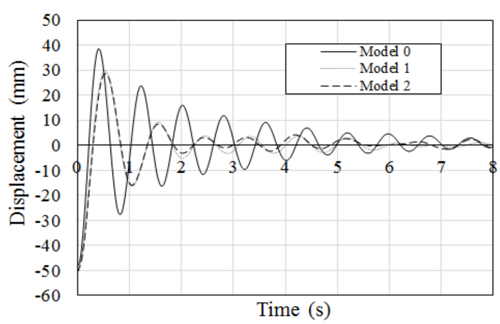

Fig. 4. Heave motion for models with various thickness

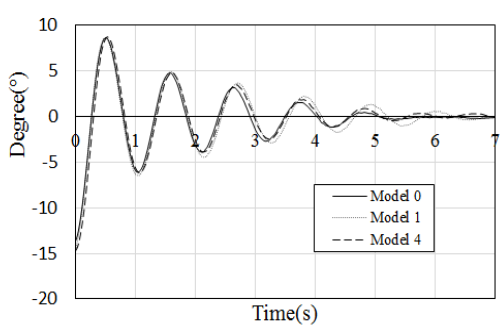

Fig. 5. Pitch motion for models with various diameter

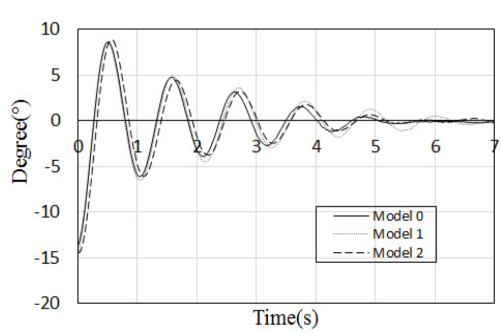

Fig. 6. Pitch motion for models with various thickness

Phillip et al.[6] conducted free decay test using different spar–buoy structure. The measured added mass coefficient and damping ratio are shown in Table 4.

As shown in Tables 3 and 4, the (spar–buoy) cylinder has relatively low added mass coefficient, whereas the added mass coefficient increases up to around 0.2 when having the heave plate on the bottom of the cylinder. In addition, since the heave plate is installed apart from the bottom of the cylinder by the thin rod, the separated heave plate has more efficient performance to increase the heave added mass compared to those of Phillip et al.[6]

In terms of damping effect, heave plate shows better effect on enhancing the damping ratio of

Table 3. Heave added mass coefficient for experimental model

Models	Heave damped period (s)	Added mass coefficient (C_a)	Damping ratio (%)
Model 0	0.78	0.030	4.3
Model 1	0.89	0.255	9.1
Model 2	0.90	0.271	11.1
Model 3	0.87	0.220	7.1
Model 4	0.86	0.202	6.4

Table 4. Heave natural period and added mass coefficient (Ca) in free decay experiment (Phillip et al.[6])

Models	Heave natural period (s)	Heave added mass coeff. (C_a)	Damping ratio (%)
Spar	1.35	0.077	4.2
spar with heave plate (bottom)	1.47	0.222	10
spar with heave plate (0.5D from bottom)	1.43	0.168	8.9

spar–buoy structure. The damping ratio for the Models 1 and 2, which installed with a larger diameter heave plate, increases by 212% and 258%, respectively, when compared with the single spar, Model 0. To give a summary of the Table 3, the larger diameter and thinner heave plate indicates relatively better damping effect on suppress the heave motion of models.

The results from Phillip et al.[6] also shows the similar tendency of the effects of heave plate on damping ratio.

3.2 Motion response

In this study, the wave amplitude, heave and pitch motion responses were also calculated by applying the LSM (Least Square Method) curve–fitting and Taylor series expansion. As shown in Figs. 7–10, the Response Amplitude Operator (RAO) for the heave and pitch motion with a variety of parameters such as diameter, thickness of heave plate were acquired and analyzed in our floating models. Depending on the parametric cases, the comparison was made with different group. The abscissa of figures denotes the non–dimensional wave period λ/L.

A series of regular waves were generated for all the models over a range of wave periods from 0.51s to 1.24s. The dispersion relation is given by:

$$\lambda = \frac{gT^2}{2\pi} \tag{10}$$

The corresponding wave period and the non–dimensional quantity λ/L, where L is equal to diameter of cylinder for this study, are also given

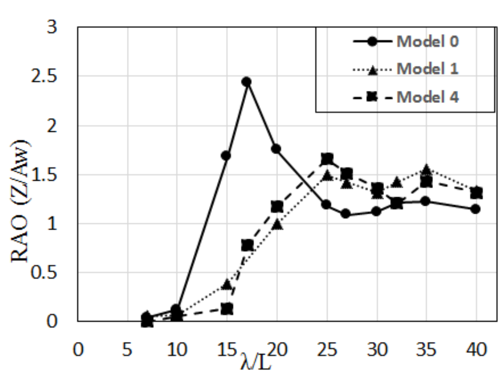

Fig. 7. Heave motion response for models with various diameter

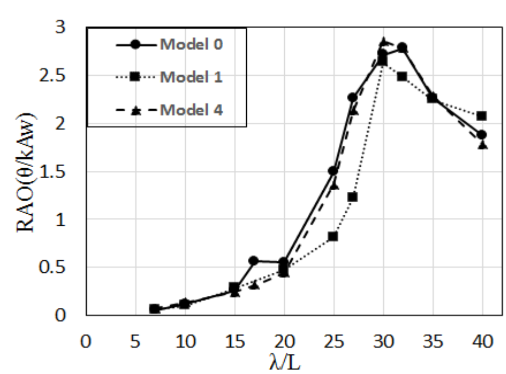

Fig. 9. Pitch motion response for models with various diametera

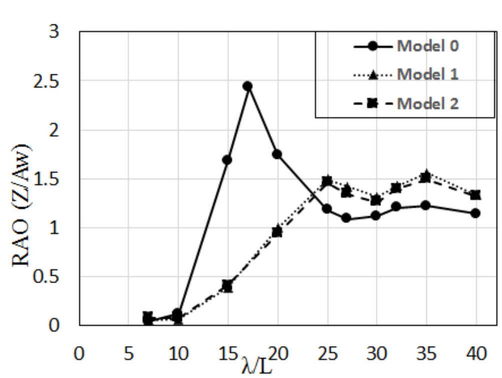

Fig. 8. Heave motion response for models with various thickness

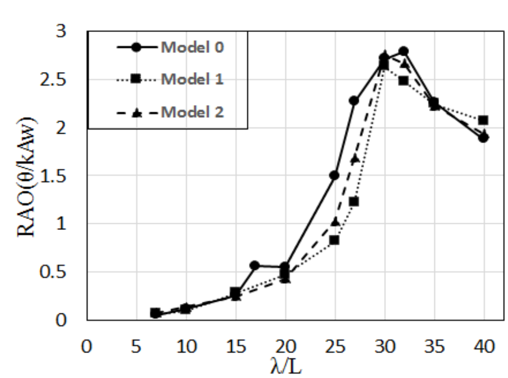

Fig. 10. Pitch motion response for models with various thickness

Table 5. The non-dimensional ratio to the wave period

λ/L	7	10	15	17	20
T (s)	0.51	0.62	0.76	0.81	0.88
λ/L	25	27	30	35	40
T (s)	0.98	1.01	1.07	1.18	1.24

in Table 5.

In Figs. 7 and 8, the model 0 (base model) shows a dominant peak RAO at $\lambda/L \cong 17$, but for the model 1, 2, and 4 with heave plate the peak heave RAO value changes to $\lambda/L \cong 25$ due to the increased added mass. In addition, the peaks in heave RAO distribution are also suppressed because of the extra heave damping in model 1, 2, and 4. Regarding the damping effect, the larger diameter of heave plate shows relatively better in terms of efficiency, whereas the thickness of heave plate is little effective.

Figures 9 and 10 show the pitch RAO distribution against non-dimensional quantity λ/L, and the heave plate effect seems mostly negligible. Interestingly, it is found that a local peak in $\lambda/L \cong 17$ is due to the large heave motion so that the heave motion could enhance the pitch motion in the heave resonant region.

4. Conclusions

An experimental study based on the response of a vertical cylinder with a separated heave plate in the regular waves was conducted on scaled models in a laboratory wave flume. The influence of heave plate on the damped period and motion response has been studied. The following conclusions can be drawn from the present study.

1) The heave plate has a significant effect on enhancing damped heave period. The diameter of heave plate has relatively larger effect on enhancing the heave added mass compared to increasing the thickness of the heave plate. Larger diameter and smaller thickness of the heave plate indicates the better efficiency to suppress the heave motion of spar-buoy structure.
2) Moreover, the peak heave response amplitude operator (RAO) of the models with plate has been reduced significantly compared to a single cylinder.
3) Furthermore, a small peak Heave RAO was found in the experiments. It seems that the pitch motion has an effect on heave motion in the pitch resonance frequency.

Due to the limited facilities and time, it needs more work in the water flume in another experiment. Regarding the validation of the current experiment, the numerical simulations will be carried out to verify the experimental results in the future.

Acknowledgements

This work was supported by a 2-Year Research Grant of Pusan National University.

References

[1] Jonkman, J. M., 2007, “Dynamics modeling and loads analysis of an offshore floating wind turbine”, Ph.D. Thesis, Department of Aerospace Engineering Sciences, University of Colorado, Boulder.
[2] Sudhakar, S. and Nallayarasu S., 2011, “Influence of heave plate on hydrodynamic response of spar”, OMAE.
[3] Tao, L., Molin, B., and Scolan, Y. M., Thiagarajan, K., 2007, “Spacing effects on hydrodynamics of heave plates on offshore structures”, Journal of Fluids and structures, 23, pp. 1119-1136.

[4] Prislin, I., Blevins, R. D., and Halkyard, J., 1998, “Viscous damping and added mass of solid square plates”, Proceedings OMAE Conference, Lisbon.

[5] Molin, B., 2001, “On the added mass and damping of periodic arrays of fully or partially porous disks”, J. Fluid and Structures. 16, pp. 1-16.

[6] Phillip, N. T., Nallayarasu, S., Bhattacharyya, S. K., 2012, “Damping characteristics of heave plates attached to spar hull”, OMAE.