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실린더형 부유식 수직축 풍력발전시스템의 동적 안정성 및 계류 안정성에 관한 연구

A Study on the Dynamic Stability and Mooring Stability of the Cylindrical Floating Vertical Axis Wind Turbine

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A Study on the Dynamic Stability and Mooring Stability of the Cylindrical Floating Vertical Axis Wind Turbine

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Abstract

The effort of reducing the carbone dioxide emission, the problems for fossil fuel and nuclear, a number of investigation to new and renewable energy is dramatically increasing. One of them, The wind power generation systems currently installed on seas are divided into fixed and floating structures according to their support structures. Among various type of floater, the cylindrical structure has a very long period of heave and pitch motion response on the ocean waves. To get the dynamic stability of the cylinder structure, it is required to obtain suitable metacentric height (GM). However, the structure has sufficient metacentric height, when the natural frequency of heave motion is doubled with the natural frequency of roll and pitch motion, the Mathieu instability can be arisen. This paper carried out numerical calculation and experiment regarding vertical axis wind turbine with cylindrical floater which has three different center of gravity. In the regular wave experiment, divergence of the structure motion without Yaw is observed when natural frequency of the heave motion is doubled with the natural frequency of roll and pitch motion. Upon the result of tension response in regular wave experiment with catenary mooring system, the mooring lines in the front of the structure have a bigger tension effect to the offset of the structure than the mooring lines at the back of the structure. In the irregular wave experiment, the motion spectra of structure motion are compared with each different center of gravity and one of the motion spectra of structure is very high when the natural frequency of heave motion is doubled with the natural frequency of roll and pitch motion. The dynamic response spectrum of the structure in the irregular wave experiments showed no significant differences in response following difference of mooring system. As a result of the comparison of the tension response spectrum, the mooring lines have a greater value for heave motion, as shown in the previous regular wave experiment. The results of the dynamic response of the structure in irregular wave and wind, Heave motion response is influenced by the couple effect with the mooring lines by the surge and pitch motion. Also offset of the structure due to the wind, the mooring lines in front of the structure have a very large tension force compared to the mooring lines in front of the structure.

KEY WORDS: Floating Vertical Axis Wind Turbine 부유식 수직축 풍력발전시스템, Cylindrical Structure 실린더형 구조물, Mathieu instability 매튜 불안정, Metacentric height 메타센터 높이, Dynamic Stability 동적 안정성, Mooring system 계류시스템, Foot print radius 계류설치반경

CHAPTER 1 INTRODUCTION

1.1 Background

The effort of reducing the carbon dioxide emission, which is the problems for fossil fuel and nuclear, a number of investigation to new and renewable energy is dramatically increasing. One of them, the wind energy, is recognized the most efficiency method and its installation is constantly increasing in Europe, America and China. The region of installation of wind generation system is divided into onshore and offshore. In case of onshore, many problems are indicated such as noise, view and mass of wind. Due to those problems, nowadays, its installation sites are moved to offshore.

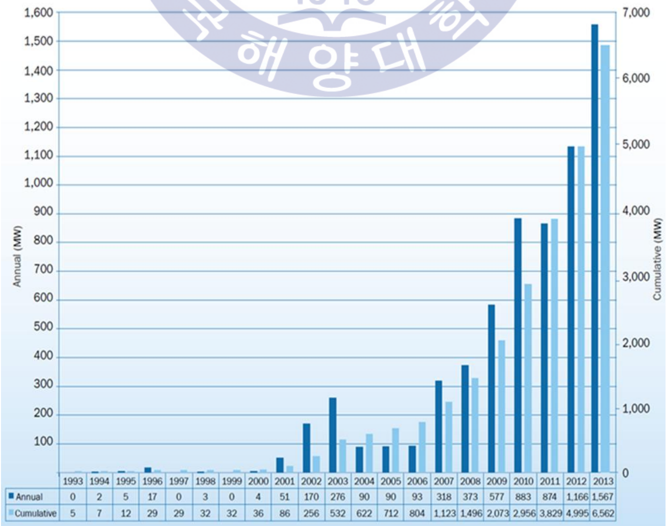

Fig. 1.1 Cumulative and annual offshore wind installations (MW), EU

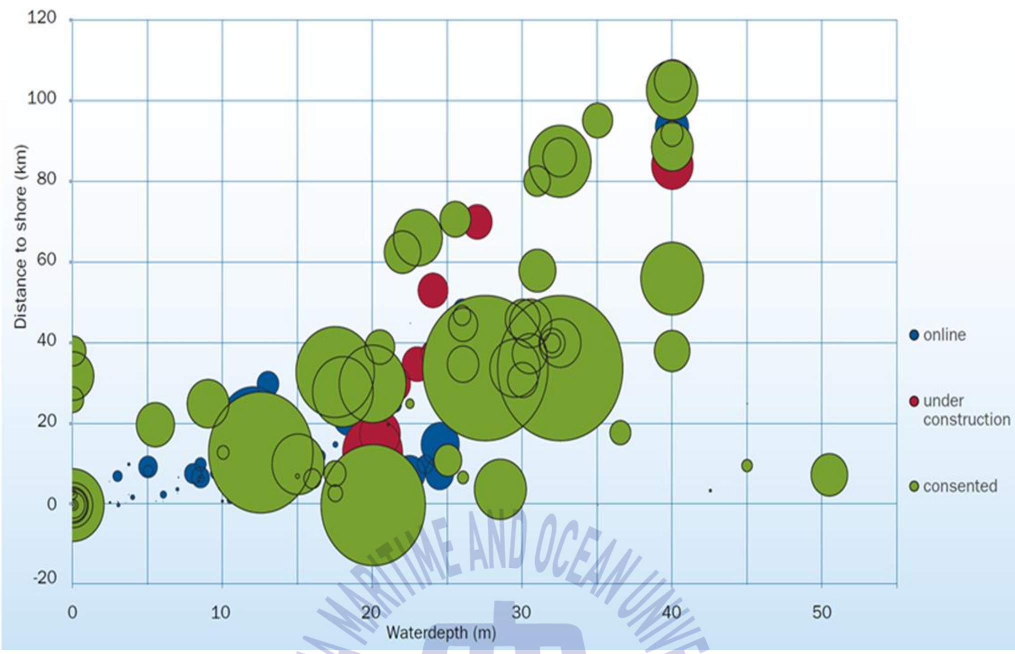

Fig. 1.2 Average water depth and distance to shore of online, under construction and consented wind farms, EU

The wind power generation systems currently installed on seas are divided into fixed and floating structures according to their support structures and are distinguished by vertical axis and horizontal axis wind power generation systems depending on the axis of rotation. The advantages of the vertical axis wind power generation systems are that its structure is relatively simple, because the yawing system and pitch control system used to enhance the efficiency of the horizontal axis wind power generation systems are not needed for vertical type, and besides Gyroscopic effect on vertical type is lower and no delay for wind direction compared to horizontal type. And also its center of gravity is located lower than horizontal type, so easy to maintain (Anagnostopoulou et al., 2016). Due to the less efficiency loss than the horizontal axis at low wind speed, the installation area has less restrictions

(Shires, 2013).

The problem of current wind power generation systems is that the characteristics of wind farms used by onshore are substantially brought to sea and applied to floating structures, despite differences in onshore and offshore conditions (Borg and Collu, 2015).

To maintain stable development efficiency of offshore wind power generation systems, it is important to maintain good dynamic performance and positioning.

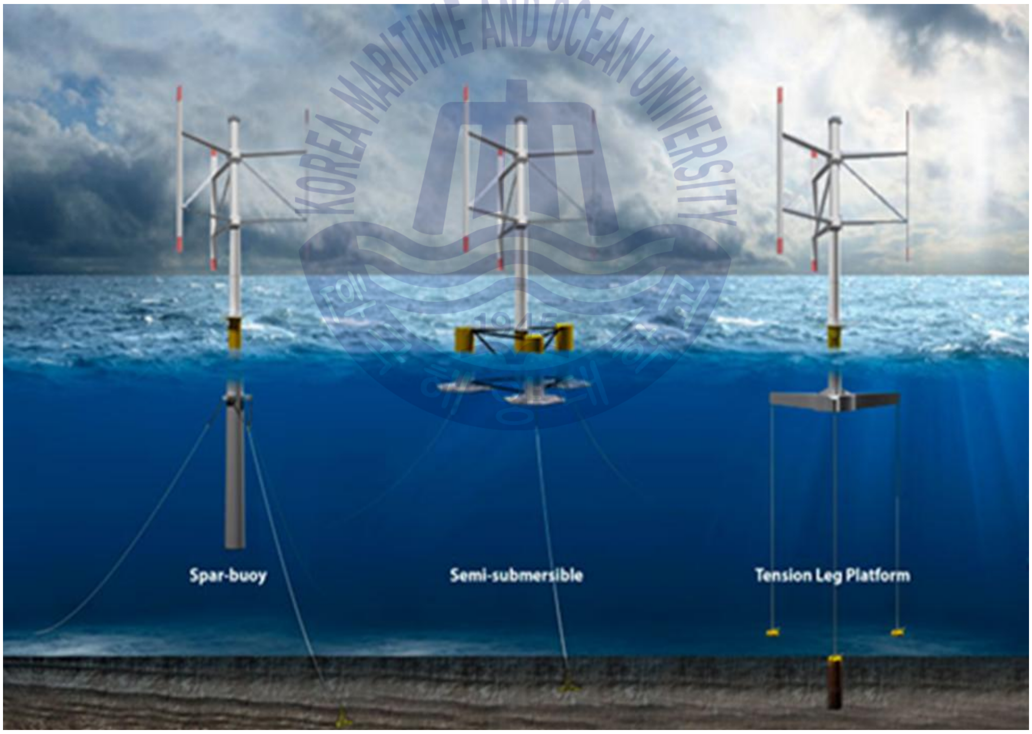

Fig. 1.3 Floating vertical-axis wind turbine concepts

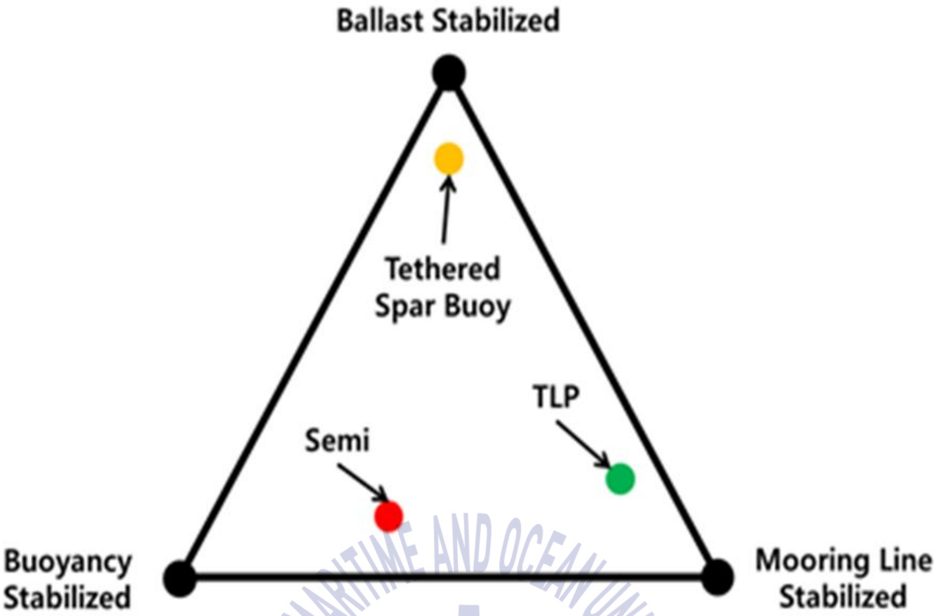

Fig. 1.4 Floating support structure stability triangle

Cylindrical structure places a center of gravity below a center of buoyancy using ballast which is located bottom of cylinder for securing dynamic stability of structure motion. The characteristics of cylindrical structure motion is that motion period is very long to avoid resonance by ocean waves. because of it, cylindrical structure can avoid Springing or Ringing phenomenon which occurs at TLP(Tension Leg Platform) but it may have slow drift motion(Oh., 2003).

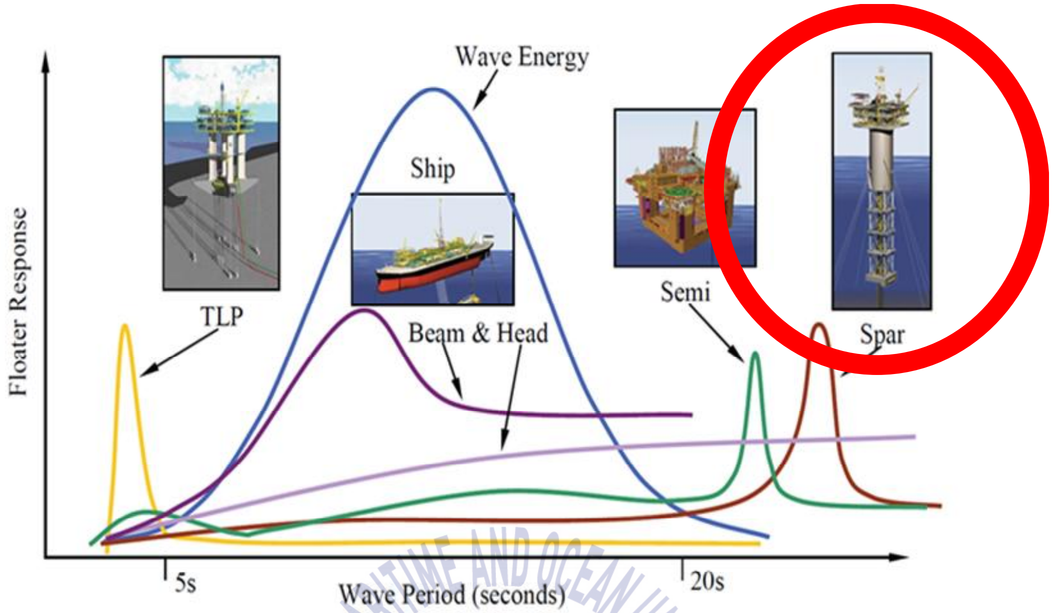

Fig. 1.5 Characteristic of each offshore platform's motion period on ocean wave

In designing cylindrical structure, The main focus is considering the location of center of gravity. Cylindrical structure has small water plane area than others, The metacentric height having a decisive effect on roll and pitch restoring moment is highly influenced by the location of center of gravity. In case of small metacentric height, The restoring moment becomes small and the structure has risk to capsize. While metacentric height is large and restoring moments are sufficient, Structure motion has possibility of resonance by Mathieu instability.

1.2 Literature review

As the previous studies, Anagnostopoulou et al. (2016) have studied the vertical axis wind power generation system consisting of two columns of two different type of Semi submersible. The motion response of the structure is analyzed using a in-house program which is applied mooring system, wind, wind and current mechanics. Collu et al. (2013) and Collu et al. (2014) developed programs applied coupling effect of wind, currents, and mooring systems, and verified that each component against the experimental results of Mertens et al. (2003). Hong et al. (1988) studied the dynamic characteristics of the structure, and compared the dynamic characteristics of the mooring line by measuring the tension force of the mooring through experiment.

The previous studies of Mathieu instability of cylindrical structure have been conducted in many years. Koo et al.(2004) have studied Spar structure’s Mathieu instability using theoretical simulation for various structures having different Riser and Mooring line. Rho et al.(2005) and Rho and Choi(2005) have conducted experimental study about Mathieu instability that the effect of damping plate. Hong et al. (2005) also studied experimental study in case of large heave motion by incident wave which has resonance frequency of heave motion that can occur Mathieu instability.

1.3 Objective and scopes

In this study, experiment and theoretical study are conducted for Cylindrical structure with VAWT(Vertical Axis Wind Turbine) which has three different center of gravity. The characteristics of the structural response and the tension response are compared through regular wave, irregular wave and irregular wave with wind experiment. In the regular wave experiment, Mathieu instability arises at incident waves which have frequency around heave natural frequency. A comparative analysis was conducted to compare the motion response and tension response depending on the center of gravity of the structure. Structure motions and mooring tension of three different center of gravity cases are compared through the irregular wave and irregular wave with wind experiment.

CHAPTER 2 MATHIEU EQUATION

2.1 Applying to cylindrical structure

Cylindrical structure's metacentric height changes continually than other offshore structures while big heave motion occurs. It means when big heave motion appears, roll and pitch restoring moment can be seriously affected by heave motion. Mathieu instability of cylindrical structure is harmonic response by big heave motion when heave natural frequency is two times of roll and pitch natural frequency.

Cylindrical structure's roll moment of inertia, added moment of inertia and metacentric height are equal to pitch one. The wave exciting force of roll motion $M_{ex4}(t)$ is zero to head sea and in case of ignoring the coupled effect with other motion, the motion equation becomes (1) and (2) (Hong et al., 2005).

$$(M_{44}+m_{44})\ddot{\phi}+C_{44}\dot{\phi}+\triangle GM(t)\phi=0 \tag{1}$$

$$(M_{55}+m_{55})\ddot{\theta}+C_{55}\dot{\theta}+\triangle GM(t)\theta=M_{ex5}\cos(\omega_e t+\varphi) \tag{2}$$

M_{44} and M_{55} are roll, pitch moment of inertia, m_{44} and m_{55} are roll, pitch added moment of inertia, C_{44} and C_{55} are roll, pitch damping coefficient, ω_e is frequency of incident wave, $\triangle$ is displacement, M_{ex5} is wave exciting force of pitch. Assuming $GM(t)$ like equation (3),

$$GM(t) \cong GM_0\left(1+\left(\frac{\delta GM}{GM_0}\right)\cos\omega_e t\right) \tag{3}$$

equation (1),(2) becomes (4),(5)

$$\ddot{\phi}+\gamma\dot{\phi}+(\omega_0^2+a\cos\omega_e t)\phi=0 \tag{4}$$

$$\ddot{\theta}+\gamma\dot{\theta}+(\omega_0^2+a\cos\omega_e t)\theta=H_{ex5}\cos(\omega_e t+\varphi) \tag{5}$$

$$\gamma=\frac{C_{44}}{M_{44}+m_{44}}=\frac{C_{55}}{M_{55}+m_{55}} \tag{6}$$

$$\omega_0^2=\frac{\triangle\cdot\ GM_0}{M_{44}+m_{44}}=\frac{\triangle\cdot\ GM_0}{M_{55}+m_{55}} \tag{7}$$

$$a=\left(\frac{\delta GM}{GM_0}\right)\cdot\ \omega_0^2 \tag{8}$$

$$H_{ex5}=\frac{M_{ex5}}{M_{55}+m_{55}} \tag{9}$$

γ is damping coefficient, ω_0 is roll and pitch natural frequency, GM_0 is metacentric height in still water, δGM is change of metacentric height in wave. Converting $\omega_e t$ to τ and substituting to equation (4), it becomes equation (10).

$$\ddot{\phi}+\mu\dot{\phi}+(\delta+\varepsilon\cos\tau)\phi=0 \tag{10}$$

$$\mu=\frac{\gamma}{\omega_e} \tag{11}$$

$$\varepsilon=\frac{a}{\omega_e^2}=\left(\frac{\delta GM}{GM_0}\right)\cdot\left(\frac{\omega_0}{\omega_e}\right)^2 \tag{12}$$

$$\delta=\left(\frac{\omega_0}{\omega_e}\right)^2 \tag{13}$$

Equation (10) is Mathieu equation which has 2π period of restoring coefficient of roll and pitch in time. The determination of the stability and instability of the mathieu equation is whether the parameter δ and ε are located in the δ-ε diagram(Park., 2013).

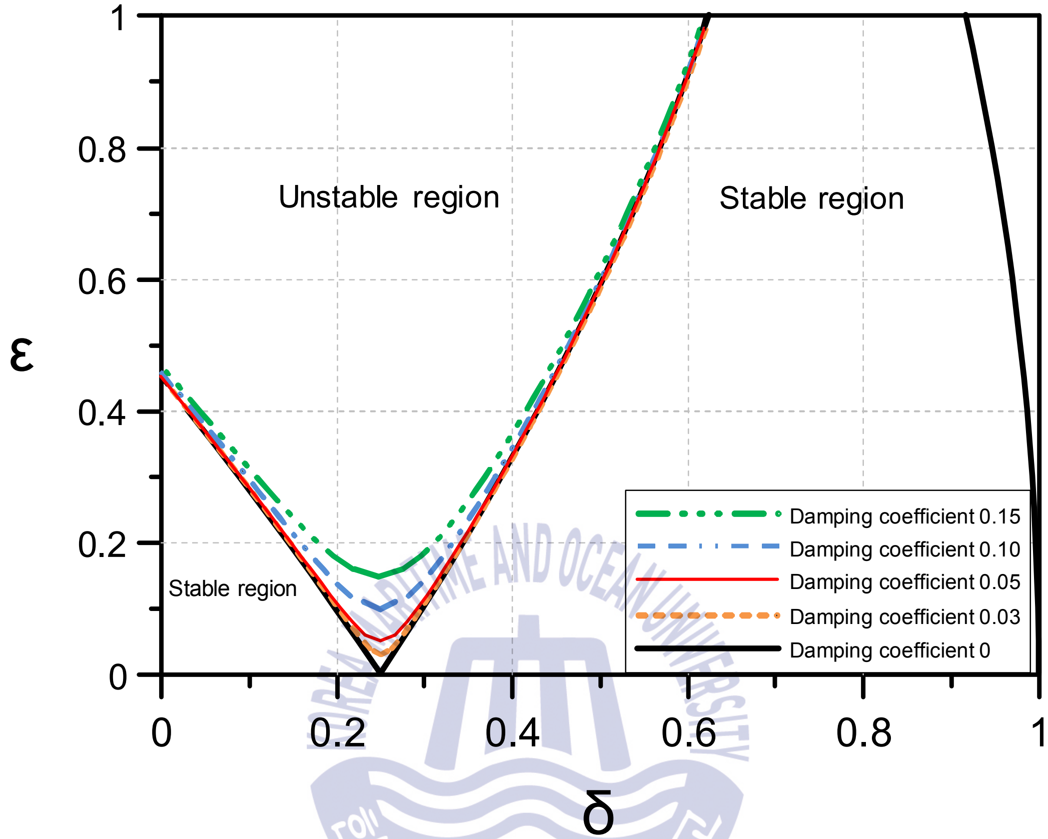

Fig. 2.1 Mathieu instability diagram

CHAPTER 3 EXPERIMENT

3.1 Experimental set-up

Experiment is conducted at three dimensional wave tank in RIMS(Research Institute Middle&Small Shipbuilding) and it has 28m length, 22m width, 2.5m depth. Structure motion is measured by 3D displacement meter.

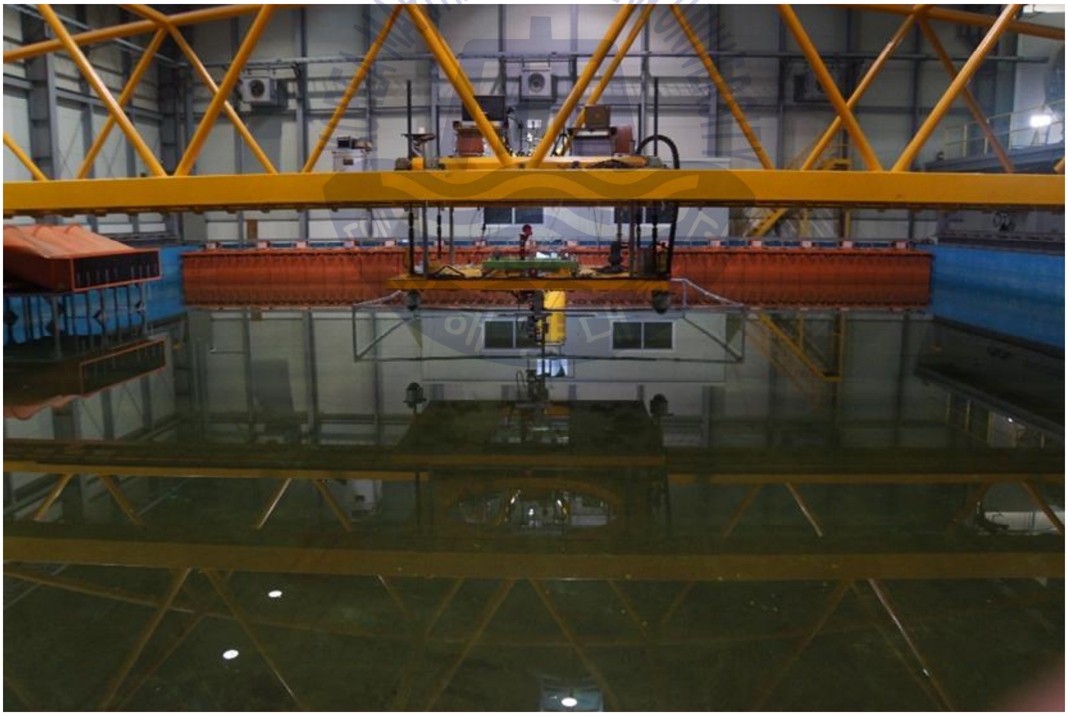

Fig. 3.1 Three dimension wave tank in RIMS

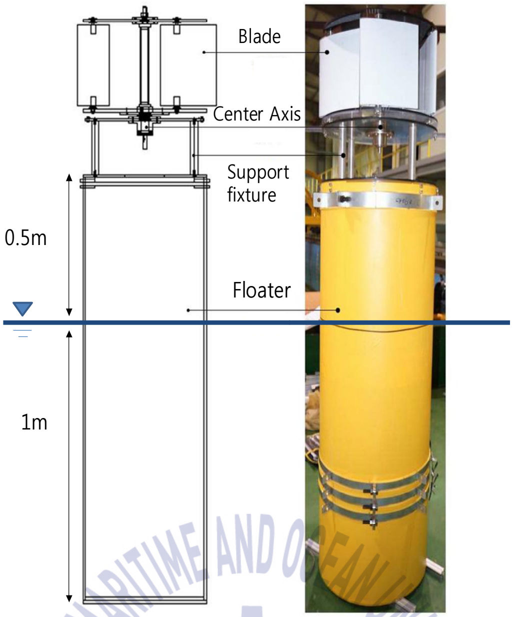

Fig. 3.2 Configuration of the experiment model

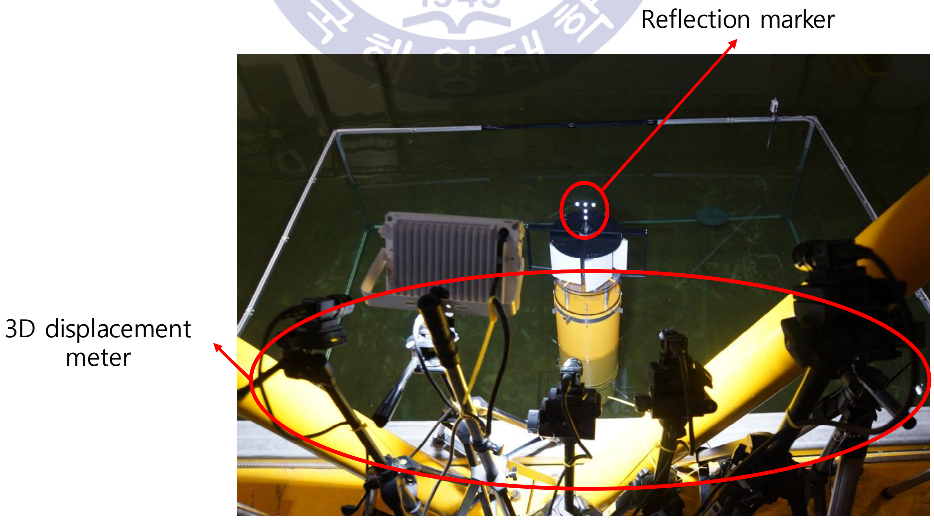

Fig. 3.3 Configuration of method of measuring structure’s displacement

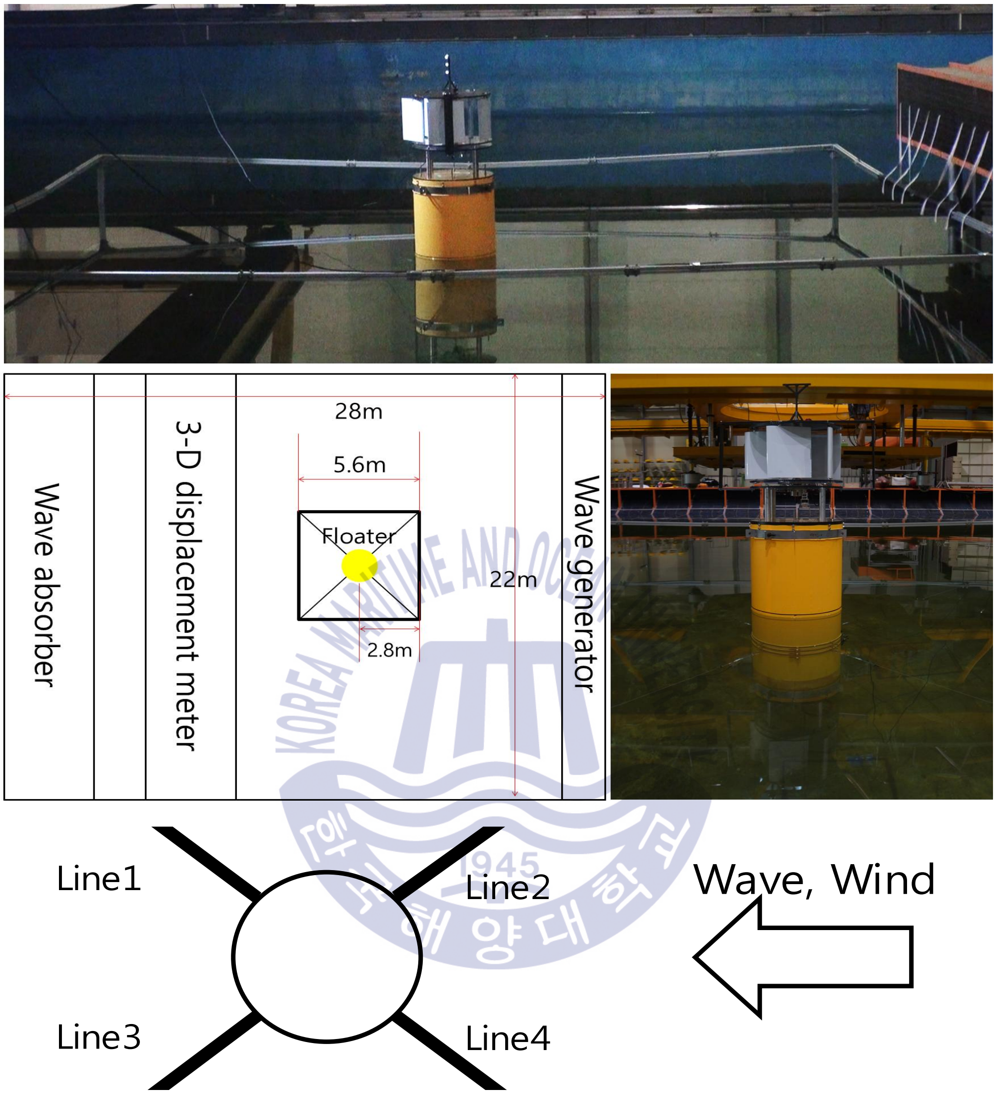

Fig. 3.4 Schematic view of experimental set-up

Fig. 3.2 shows experimental model for this study and it has 0.5m diameter, 1.5m height and 1.0m draught. Fig. 3.4 shows schematic view of the experiment. The foot print radius for mooring system is 4m. Table 3.1 and Table 3.2 show particulars of structure for each center of gravity cases. Table 3.3 shows wave height and maximum wave slope for each regular wave test. Table 3.4 shows naming of each experimental cases. The regular waves are divided into 8 cases from 2.09rad/s to 3.92rad/s. The Irregular wave is made by ITTC(International Towing Tank Conference) which has 3.58rad/s mean frequency, 0.1235m significant wave height. Table 3.5 shows the mooring characteristics. The mooring systems for station keeping are linear spring and catenary chain for experiment. Tension is measured at fairlead.

Table 3.1 Metacentric height and displacement volume following each center of gravity

KG $[m]$	Volume of displacement $[m^3]$	GML, GMT $[m]$	Remarks
0.38		0.13578	KG1
0.46	0.194386	0.05578	KG2
0.475		0.04078	KG3

Table 3.2 Moment of inertia and restoring coefficient following each center of gravity

KG	I44, I55 $[kg\cdot\ m^2]$	I66 $[kg\cdot\ m^2]$	C33	C44, C55
KG1	13.61			26.39
KG2	12.8	2.36	196.35	10.84
KG3	12.67			7.93

Table 3.3 Desired wave height and maximum wave slope

Wave period [rad/s]	Wave height (Desired) [m]	Maximum wave slope [deg]
2.09	0.1171	1.5
2.24	0.1020	
2.42	0.0879	
2.62	0.0749	
2.86	0.1259	3.0
3.14	0.1040	
3.49	0.0843	
3.93	0.0666	

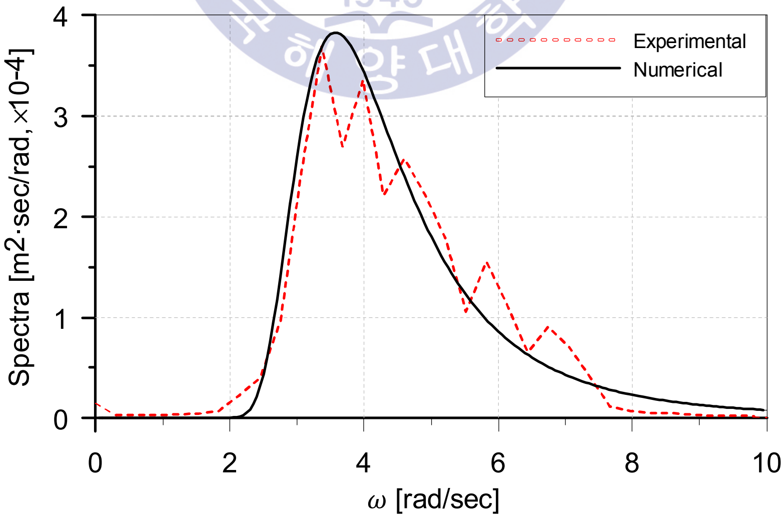

Fig. 3.5 Comparison on measured and calculated wave spectrums

Table 3.4 Experiment case

Wave type	Mooring type	Wind	KG	Case name
Regular wave	Spring	-	KG1	KG1-RW-SP
			KG2	KG2-RW-SP
			KG3	KG3-RW-SP
	Catenary		KG1	KG1-RW-CA
			KG2	KG2-RW-CA
			KG3	KG3-RW-CA
Irregular wave	Spring	-	KG1	KG1-IRW-SP
			KG2	KG2-IRW-SP
			KG3	KG3-IRW-SP
		$8.0m/s$	KG1	KG1-IRW-SP-W
			KG2	KG2-IRW-SP-W
			KG3	KG3-IRW-SP-W
	Catenary	-	KG1	KG1-IRW-CA
			KG2	KG2-IRW-CA
			KG3	KG3-IRW-CA
		$8.0m/s$	KG1	KG1-IRW-CA-W
			KG2	KG2-IRW-CA-W
			KG3	KG3-IRW-CA-W

Table 3.5 Particulars of mooring lines

Mooring type	Designation	Description
Catenary	Chain type	Studless
	Material	Stainless steel
	Diameter	0.006m
	Mass per meter	0.68kg/m
	Line length	4.2m
	Pre-tension at KG3	Line 1 : 0.7345kgf Line 2 : 0.7742kgf Line 3 : 0.7313kgf Line 4 : 0.7926kgf
Spring	Pre-tension	Line 1 : 1.865kgf Line 2 : 1.668kgf Line 3 : 1.641kgf Line 4 : 1.880kgf

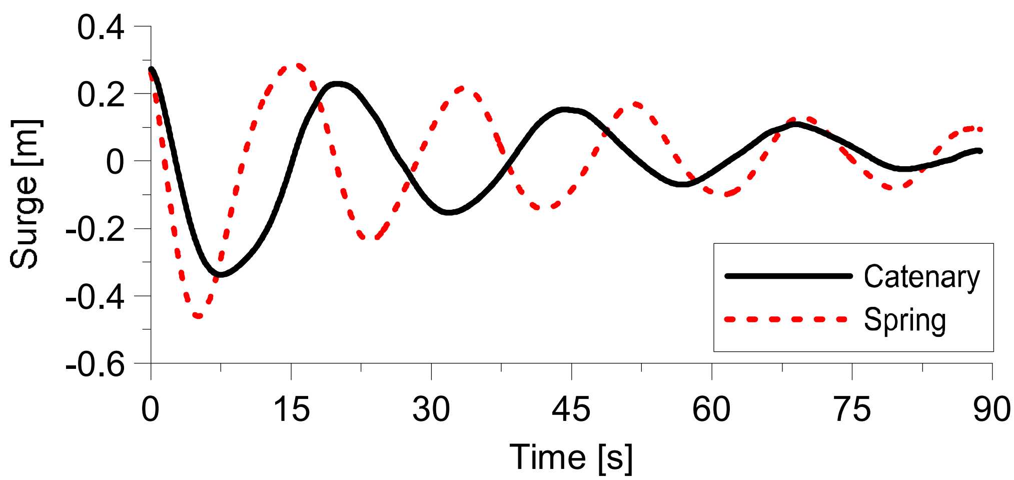

Fig. 3.6 Freedecay test of surge at KG3

Fig. 3.6 is freedecay test of surge after equipped 4 mooring lines on the structure. The natural period of spring system is 18.4 second and catenary system is 24.5 second.

CHAPTER 4 RESULT AND DISCUSSION

4.1 Result of regular wave experiment

Fig. 4.1, Fig. 4.2 and Fig. 4.3 show the result of regular wave experiment and simulation based on potential theory. In case of heave motion, it has same natural frequency even though the center of gravity changed. The natural frequency of surge and pitch has different natural frequency of changing center of gravity and it is indicated at Table 4. In case of KG1, Heave natural frequency is two times to pitch natural frequency and it corresponds with condition of mathieu instability.

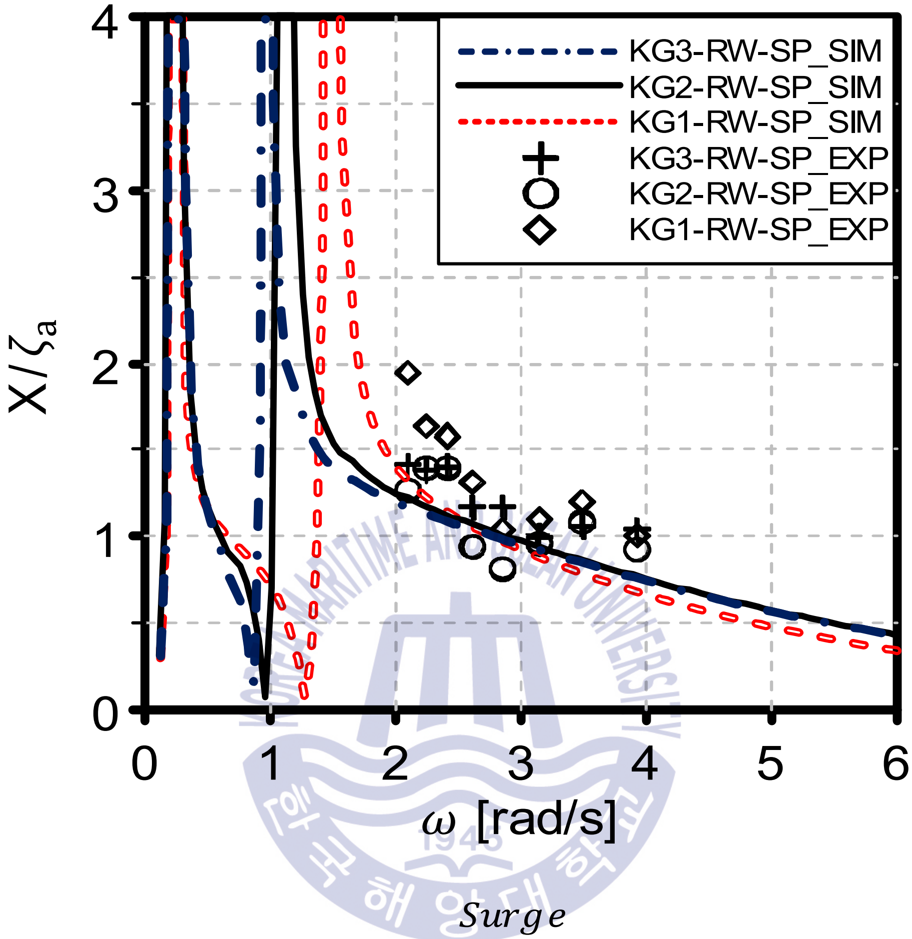

Fig. 4.1 Comparison between simulation and experiment results, Surge

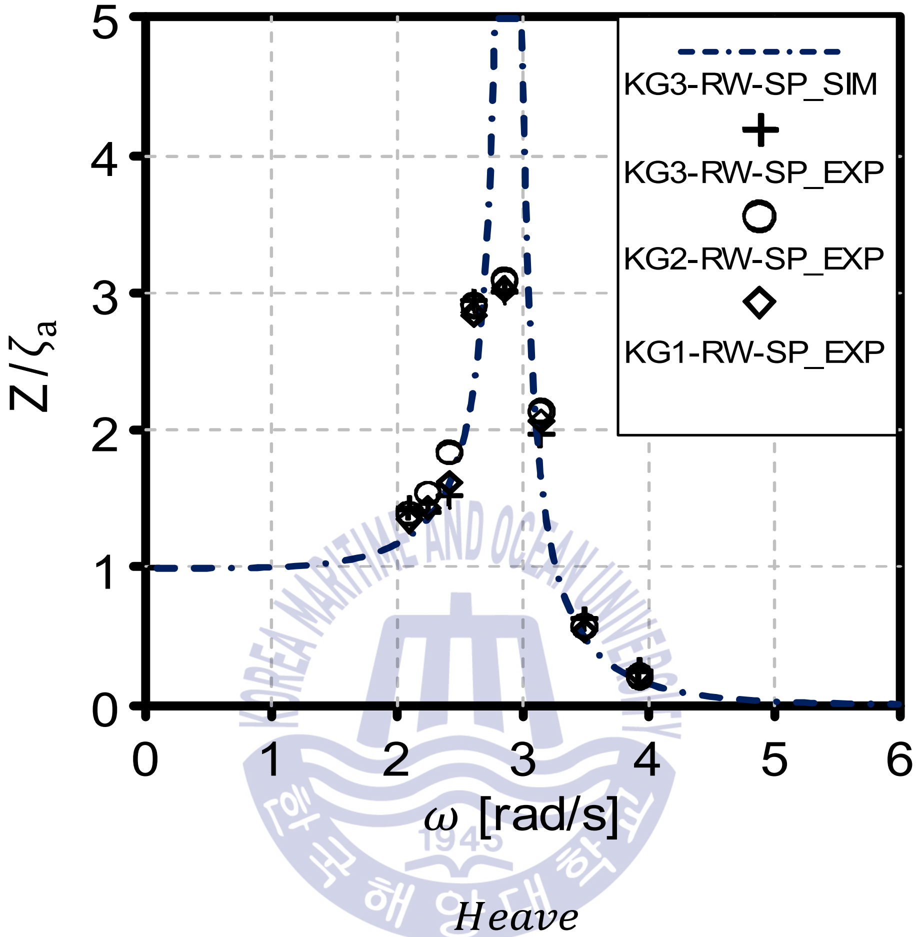

Fig. 4.2 Comparison between simulation and experiment results, Heave

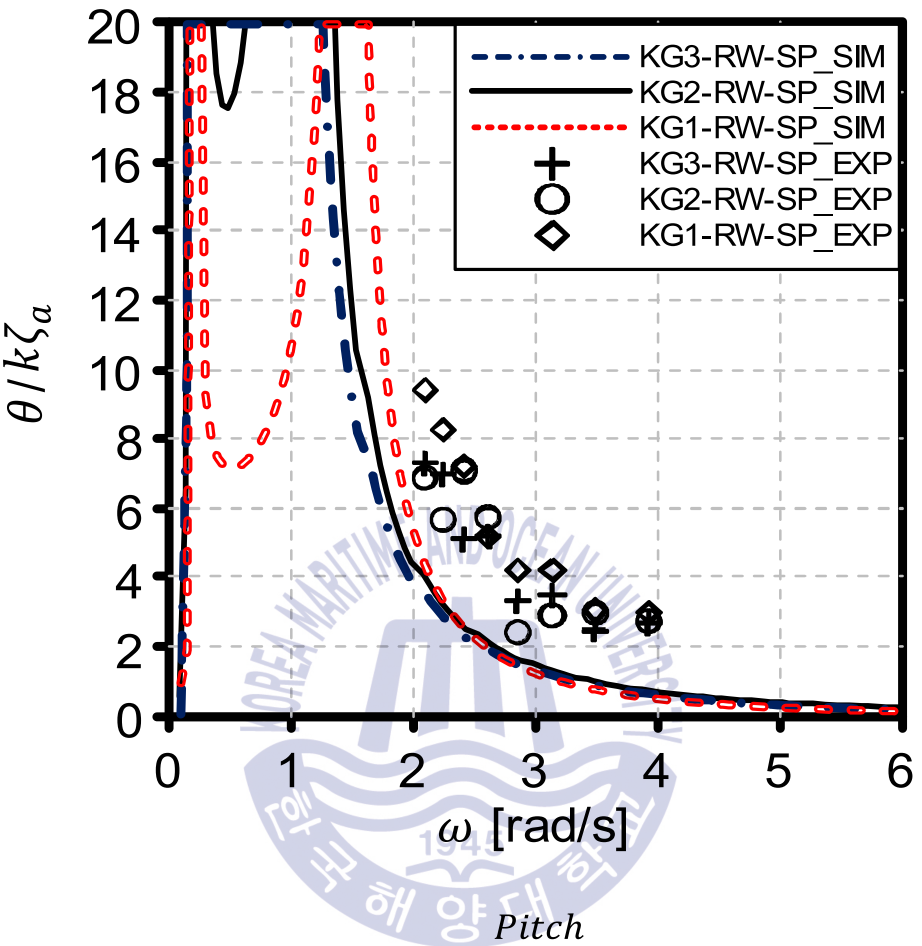

Fig. 4.3 Comparison between simulation and experiment results, Pitch

Mathieu instability occurrs at KG1-RW-SP Case in regular wave experiment and Fig. 4.4 shows the time history of structure motion in KG1-RW-SP and KG2-RW-SP case. Motions in KG2-RW-SP case are steady but the motions of KG1-RW-SP case start to be diverged around 20 seconds. Sway and roll motion are also diverged despite the head sea.

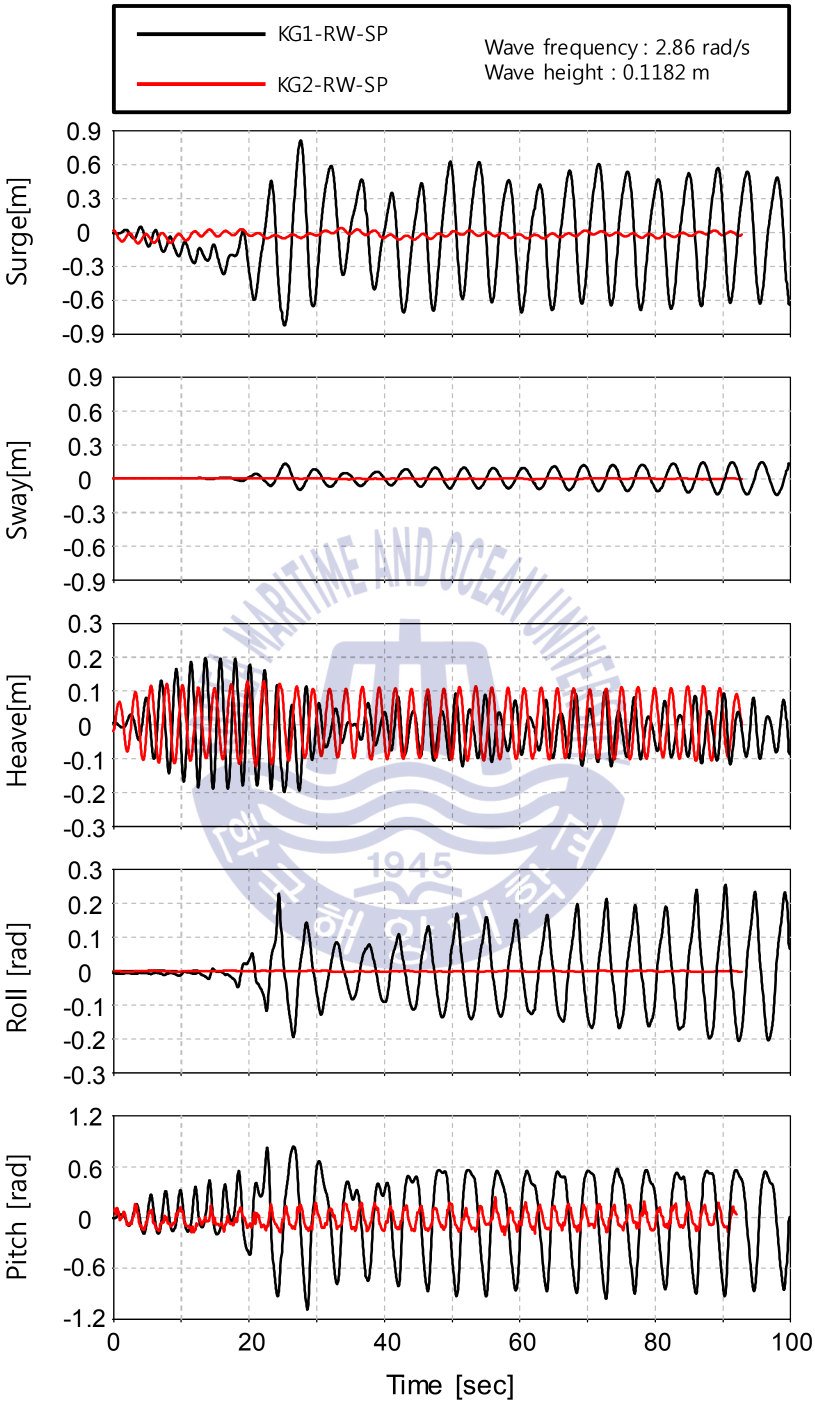

Fig. 4.4 Time history of motion in experiment (regular wave)

Fig. 4.5 shows the Mathieu stability diagram with experimental result which is calculated through the particulars of experimental model. The points on unstable region are the results of experiment in 2.62rad/s, 2.86rad/s and 3.14rad/s regular waves. Although KG1 case has biggest center of gravity, the motions on the wave are unstable. This result indicates that having a big metacentric height is not the way to secure the dynamic stability of structure. Damping coefficient getting bigger, the unstable region is reduced in δ-ε diagram and it indicates damping coefficient can supress the mathieu instability.

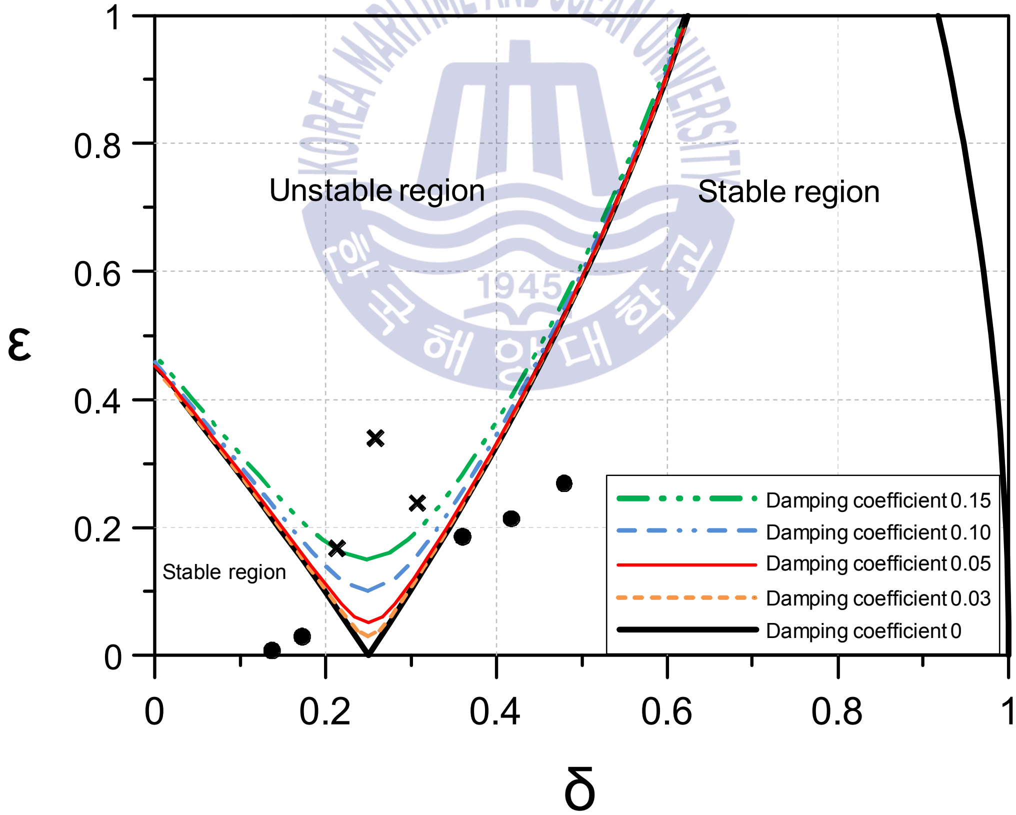

Fig. 4.5 Comparison between Mathieu stability diagram and experiment results (KG1-RW_SP)

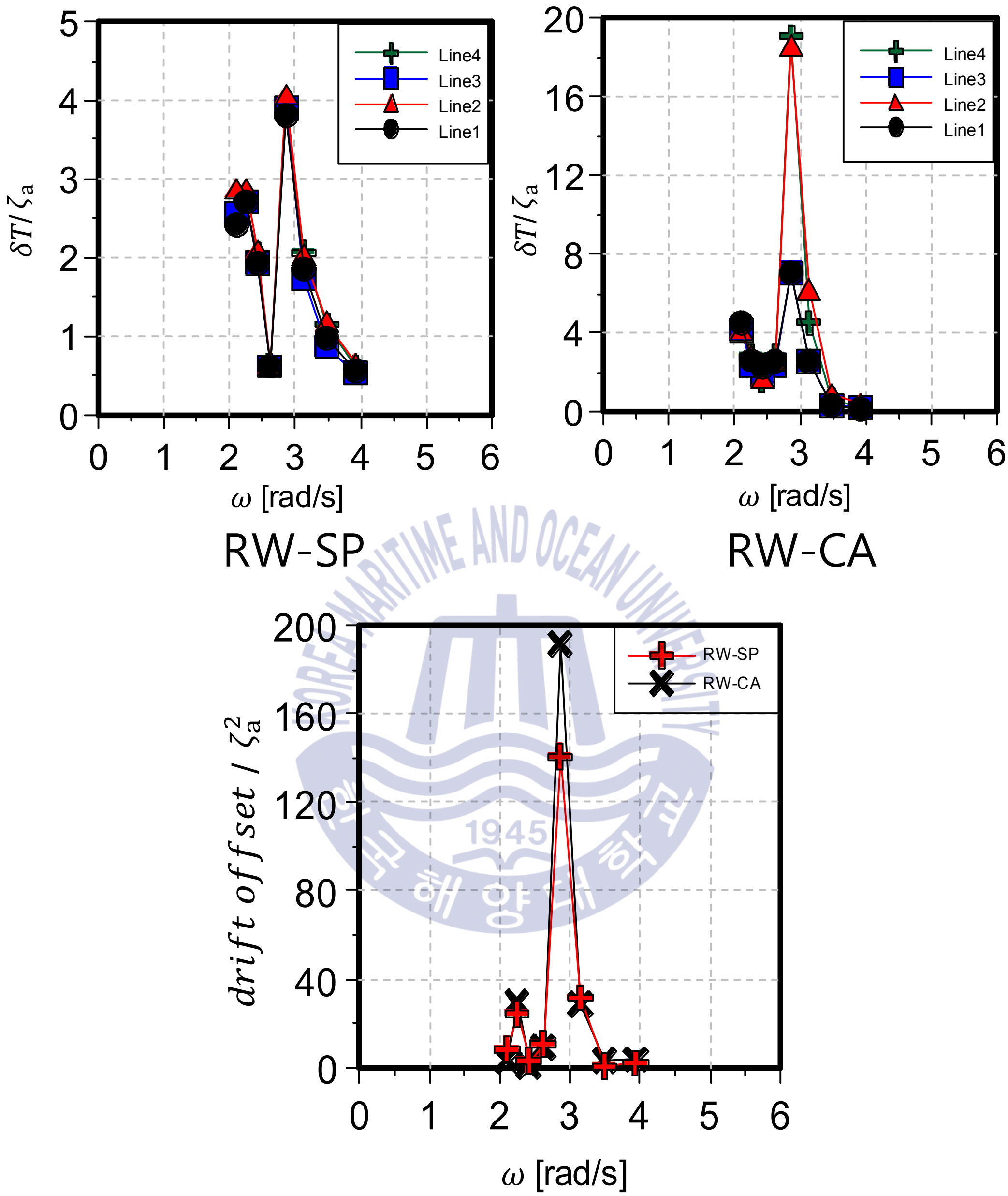

Fig. 4.6 The ratio of dynamic amplitude of tension response to wave amplitude(Line 1,3 = back, Line2,4 = front) and drift offset

FIg. 4.6 shows the values of height of tension response into wave height in KG3-RW-SP. The tension response in spring mooring system, there is no difference in each mooring lines. It has the peak values at 2.24rad/s and 2.86 rad/s, the former peak is due to surge motion while the latter peak is due to heave motion. And it also has the peak values at 2.24rad/s and 2.86rad/s for catenary mooring system, but unlike spring mooring system, it has bigger tension response about heave motion. This result is from insufficient foot print radius and shallow water effect. Furthermore, it is shown that there is a significant difference of tension response which is attributable to the nonlinear restoring force of catenary mooring characteristic between the front of the structure and the back of the structure.

4.2 Result of irregular wave experiment

Fig. 4.7 shows the time history of surge, heave and pitch motion at KG1-IRW-CA and KG2-IRW-CA Case. At the KG1-IRW-CA Case, Surge and pitch motion start to be diverged around 55 seconds. It is because of large change of metacentric height due to large heave motion by high wave height.

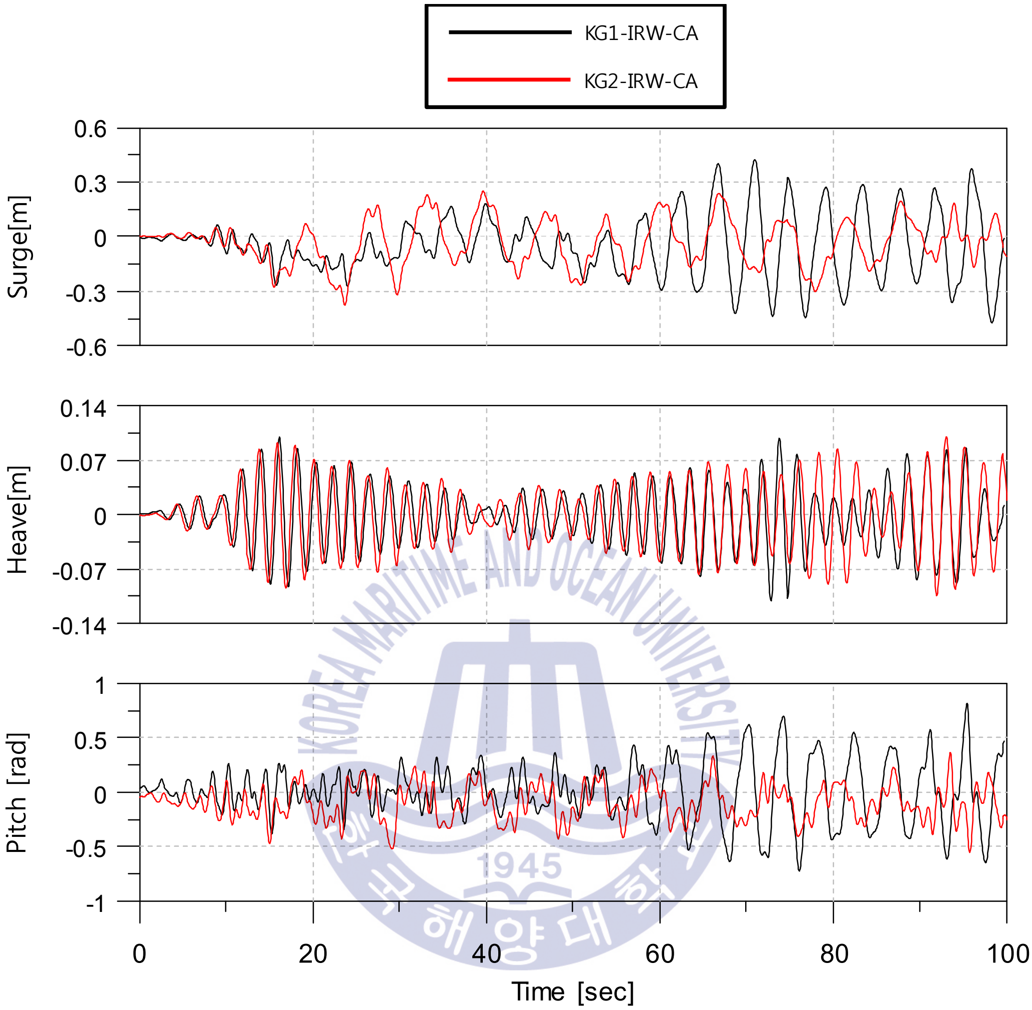

Fig. 4.7 Time history of motion in experiment (irregular wave)

Fig. 4.8, Fig. 4.9 and Fig. 4.10 show the motion spectrum for each center of gravity cases in irregular wave experiment. Heave motions in fig. 4.9 have nearly same trend for each center of gravity cases. Surge and pitch motions in fig. 4.8 and fig. 4.10 have different trend for KG1-IRW-CA because of the mathieu instability and it has very high spectral magnitude.

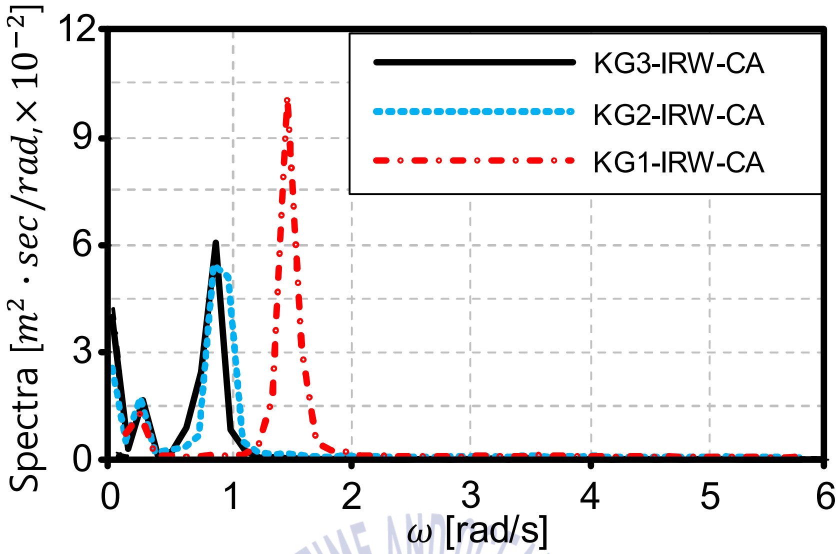

Fig. 4.8 Comparison on each experimental results in irregular wave, Surge spectra

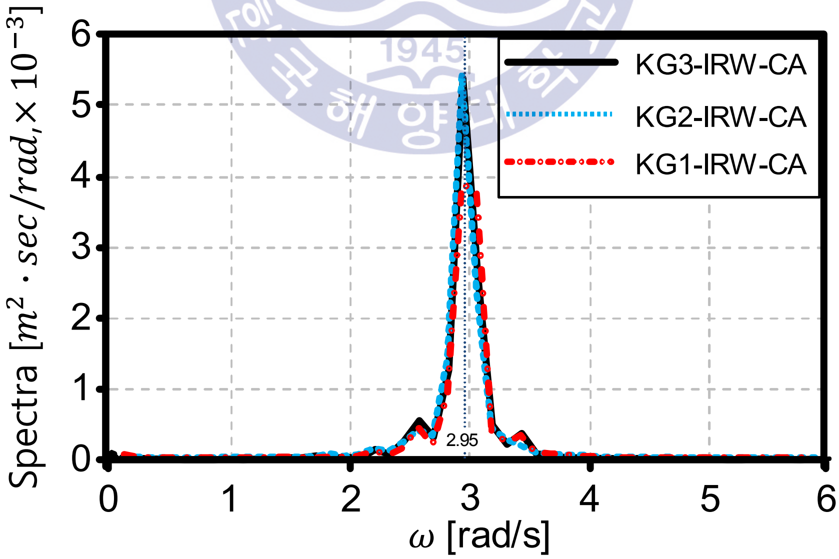

Fig. 4.9 Comparison on each experimental results in irregular wave, Heave spectra

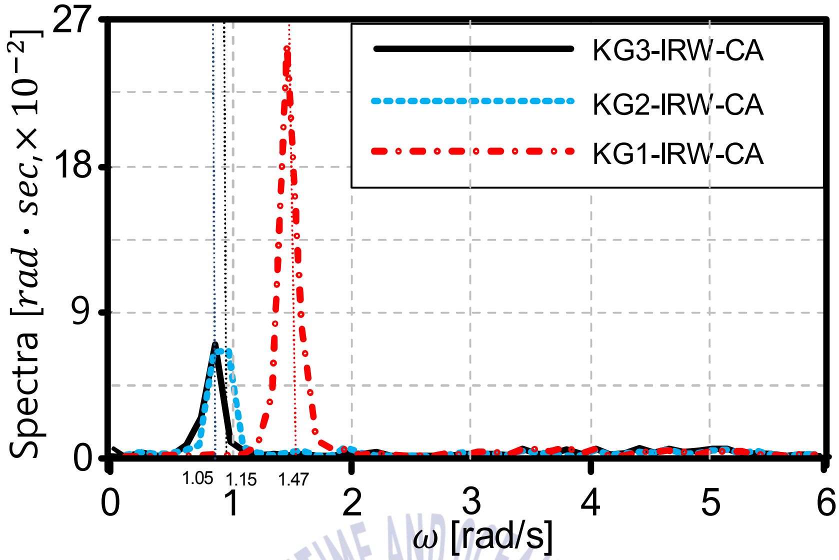

Fig. 4.10 Comparison on each experimental results in irregular wave, Pitch spectra

Fig. 4.11 and Fig. 4.12 show the comparison on motion spectrum and tension spectrum of structure in spring mooring system and catenary mooring system in irregular wave. The result of Fig. 4.11, there is no significant difference accorfing to mooring system but the result of Fig. 4.12, catenary mooring system has large effect for structure motion in irregular wave. Especially, at heave motion peak frequency 3.06rad/s, there is a peak value at same frequency due to shallow water effect and insufficient foot print radius.

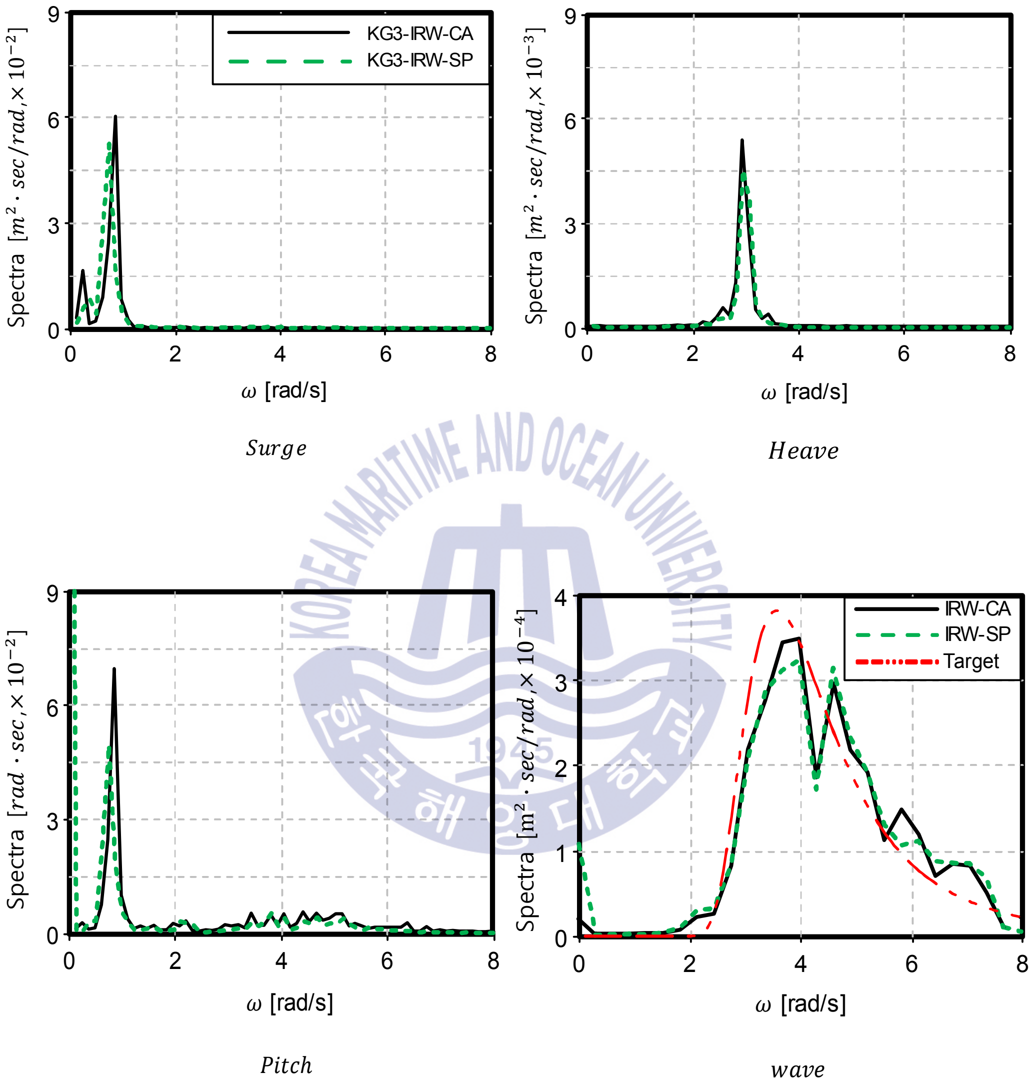

Fig. 4.11 Motion spectra and wave spectra with different mooring type in irregular wave

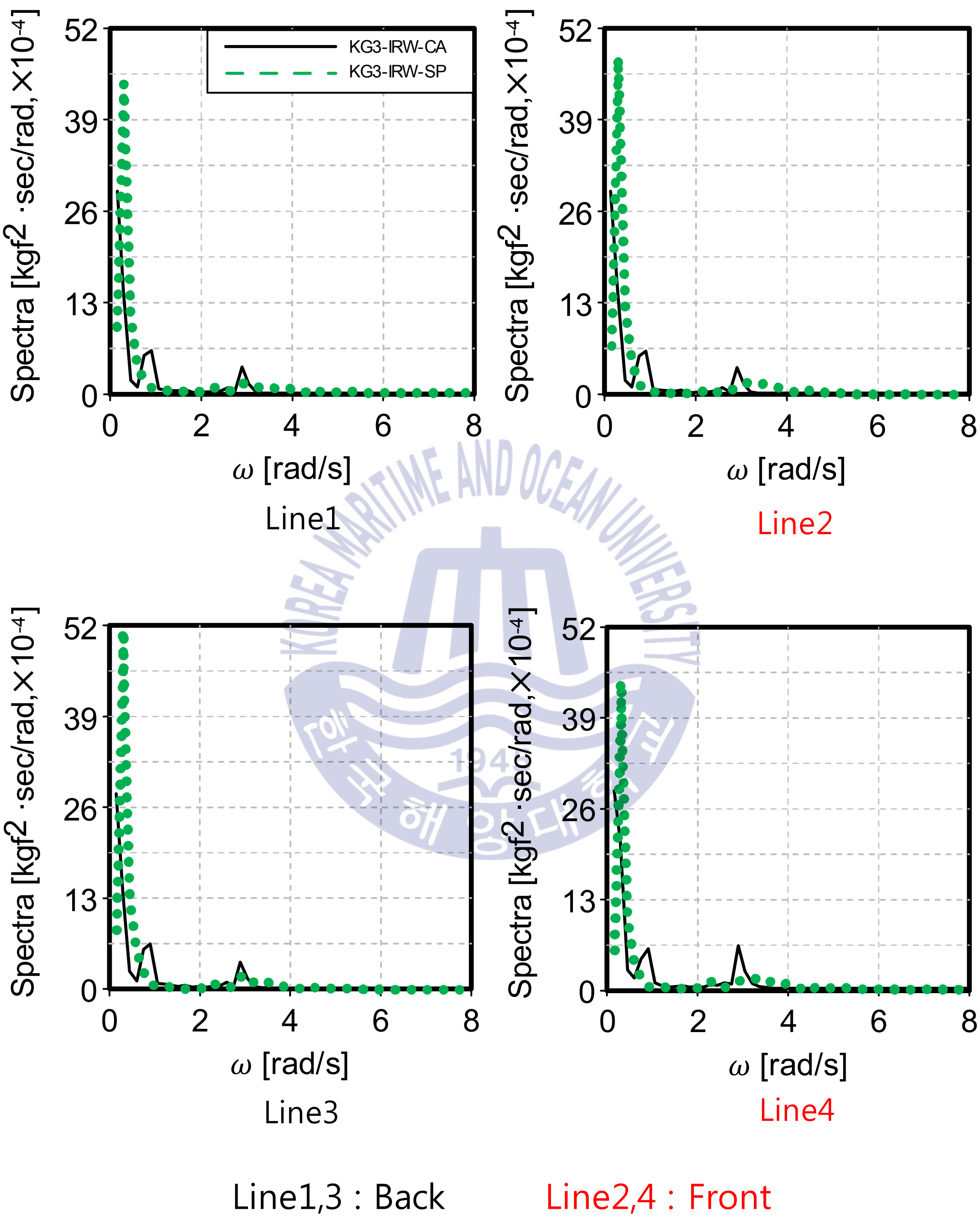

Fig. 4.12 Tension spectra with different mooring type in irregular wave (Line1,3 = back, Line2,4 = front)

Fig. 4.13 and FIg. 4.14 show the comparison on motion spectrum and tension spectrum of structure in spring mooring system and catenary mooring system in irregular wave with wind. As shown heave spectrum at Fig. 4.13, there are peak values at 0.86rad/s and 3.06rad/s in catenary mooring system, 0.76rad/s and 3.06rad/s in spring mooring system. The peak at 3.06rad/s is the heave motion in irregular wave, 0.86rad/s and 0.76rad/s are coupled effect of the mooring line due to surge and pitch motion. It is because of steady drift and steady heeling of structure by wind. Furthermore, in case of the wind load, different from the previous irregular wave experimental results, there is significant difference in motion response depending on the mooring system. For catenary mooring system, heave motion is affected by increased restoring force due to structure offset. In the case of a spring mooring, it is possible to verify that the heave motion is more responsive, resulting in a coupled effect with surge and pitch motion. As explained earlier, the steady drift and steady heeling of the structure resulted by wind affect to structure. As shown Fig. 4.14, Line 2,4 have bigger peak value than Line1,3. In particular, it has very large different peak value by surge and pitch motion, it is caused by nonlinear restoring force of catenary mooring.

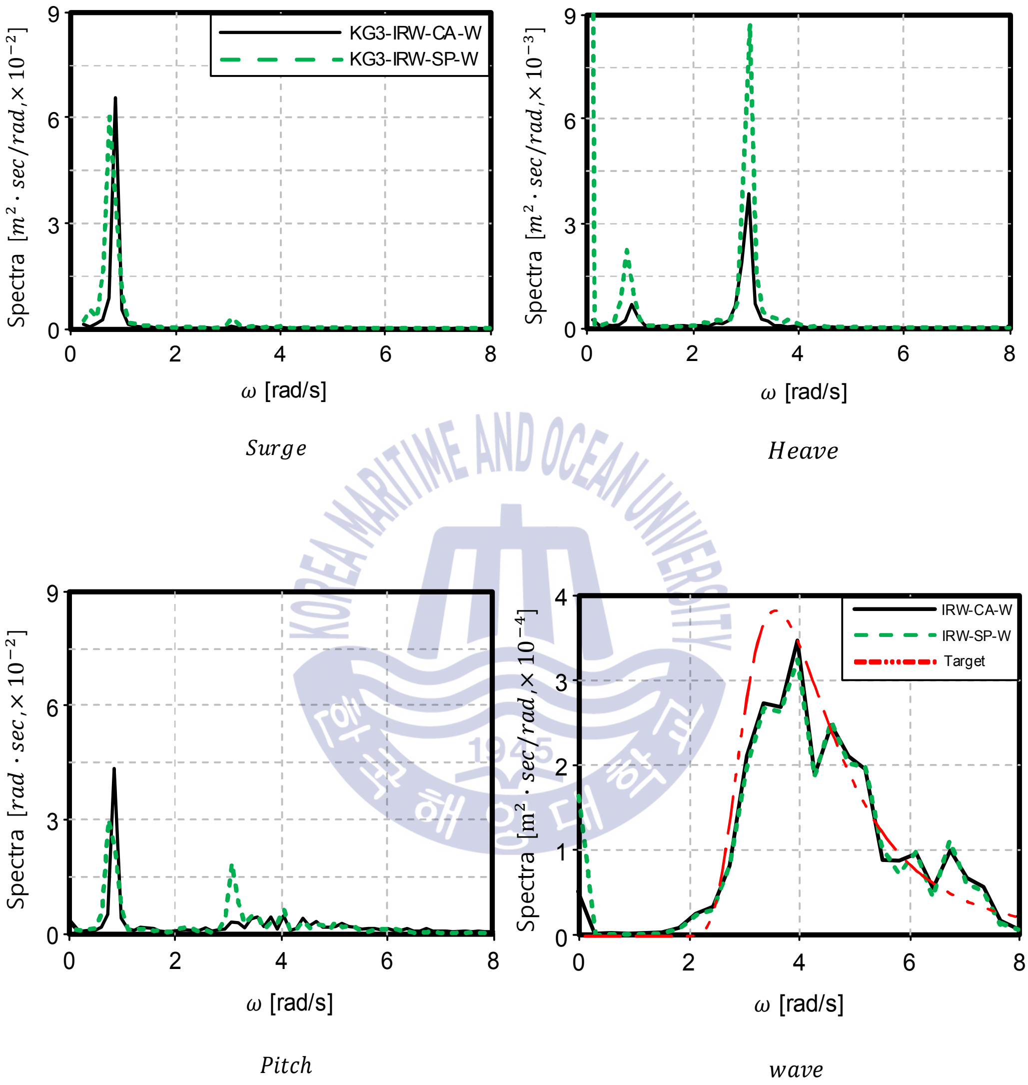

Fig. 4.13 Motion spectra and wave spectra with different mooring type in irregular wave and wind

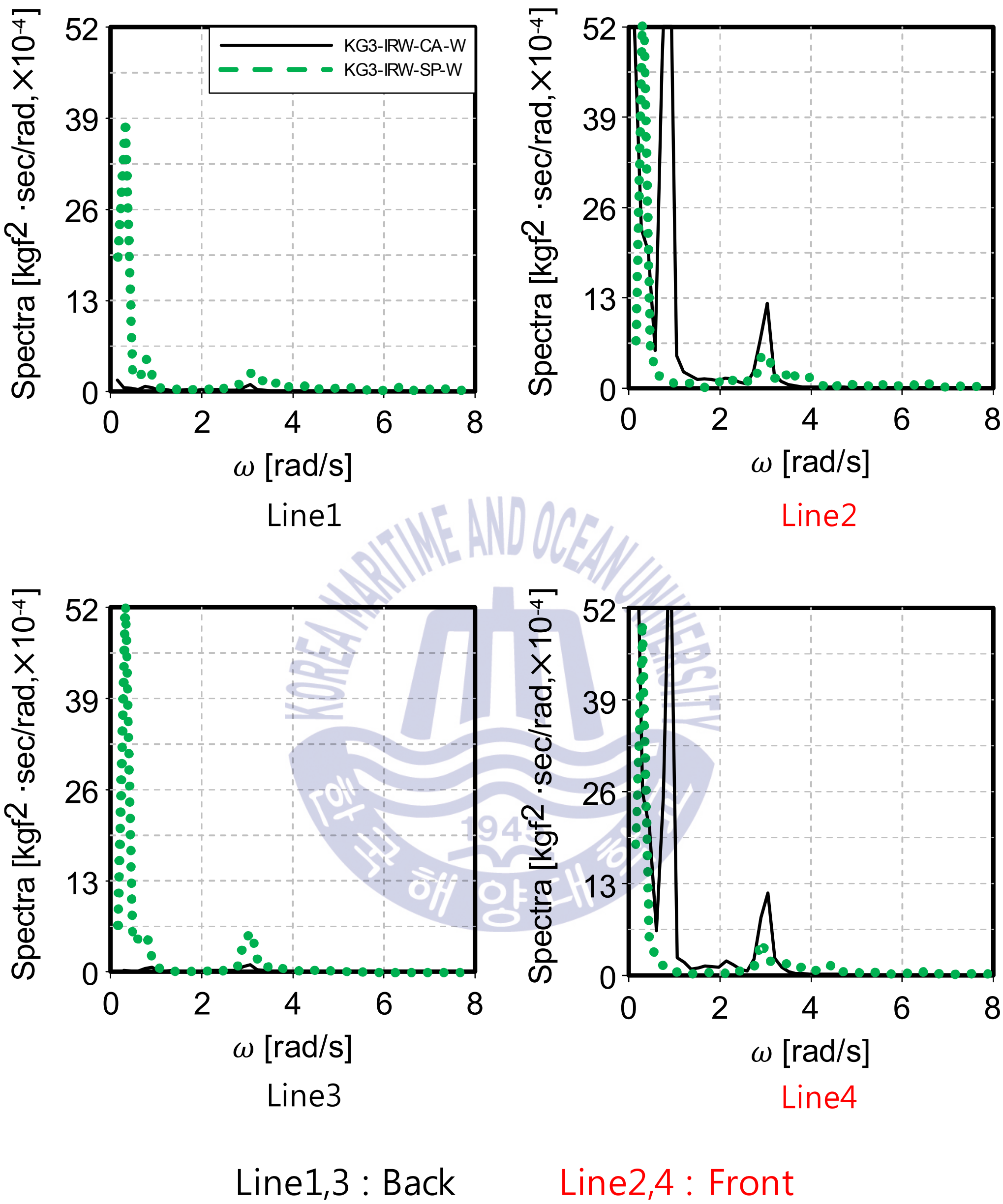

Fig. 4.14 Tension spectra with different mooring type in irregular wave and wind(Line1,3 = back, Line2,4 = front)

4.3 Statistical values of tension response

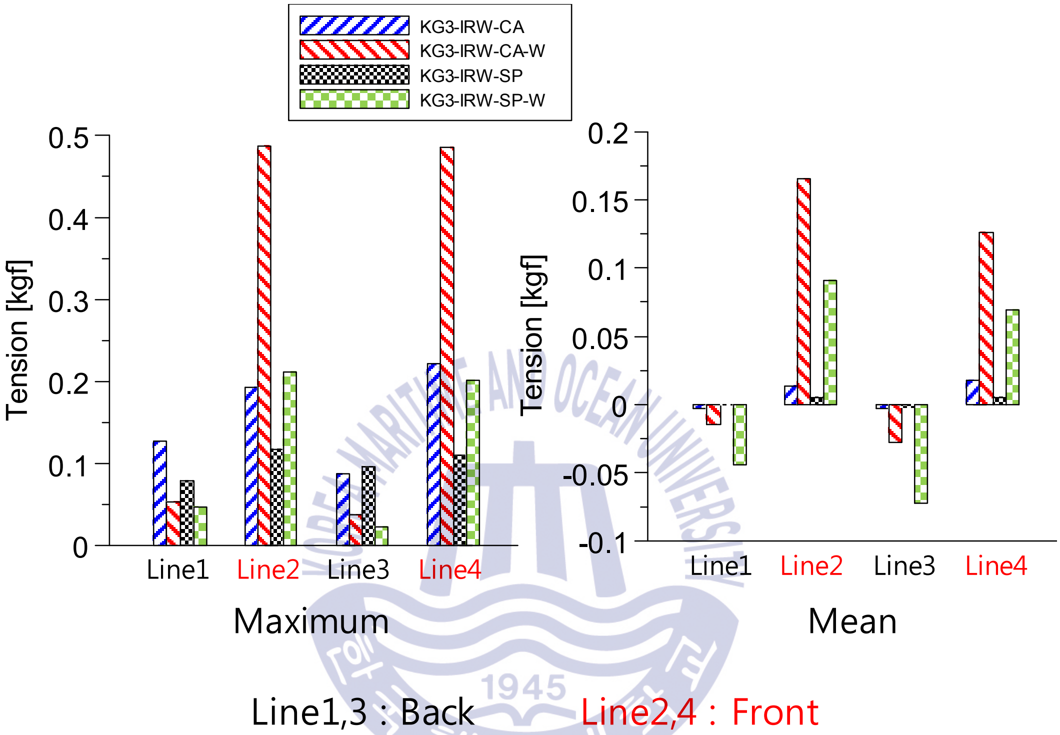

Fig. 4.15 Statistical values of tension response of each experiment cases(Line1,3 = back, Line2,4 = front)

Fig. 4.15 shows statistical values of tension response in irregular wave and irregular wave with wind experiment. In case of catenary mooring system, at line 2,4, the maximum values are 0.193kgf and 0.22kgf respectively in no wind, and the maximum values are 0.487kgf and 0.485kgf respectively in wind.

Because tension becomes very large due to wind, it is essential for having enough mooring line to avoid that tension is over MBL(Maximum Breaking Load) when designing mooring system.

Table 4.1 shows the proportion of initial and mamximum tension to maximum breaking load when it is installed at south of JEJU island.

Table 4.1 Comparison on maximum breaking load and maximum tension

	MODEL	PROTOTYPE _Theoretical	PROTOTYPE _R4 chain
Scale factor [-]	1	25	-
Diameter [m]	0.006	0.15	0.147
Mass per length [kg/m]	0.68	425	432
Initial tension [N]	7.3575	114960.94	-
Maximum tension [N]	12.13497	189608.90	-
Maximum Breaking Load [N]	-	-	19089000
Initial tension / MBL [%]		0.6022	
Maximum tension / MBL [%]		0.9932	

CHAPTER 5 CONCLUSION

This paper carried out experimental study regarding vertical axis wind turbine with cylindrical floater which has three different center of gravity. And also numerical calculation compared with experimental result for mathieu instability of KG1 case. Motion response and tension response are compared for two different type of mooring system at KG3 case. Conclusions of this study are below.

(1) This study observed that when the heave natural frequency is doubled with pitch natural frequency, Mathieu instability can be occurred by incident wave which has close frequency of heave natural frequency. It says that having a big metacentric height is not the way to secure the dynamic stability of structure.

(2) For the result of regular wave test, in case of catenary mooring system, Heave motion affects mooring tension and it is because of shallow water effect and insufficient foot print radius.

(3) Mathieu instability occurred at KG1 case in the irregular wave experiment. Through this result, Mathieu instability can also be occurred in irregular waves due to high wave height.

(4) When designing the cylindrical structure, in case of changing the structure size or loading condition, center of gravity is needed to consider to avoid Mathieu instability.

(5) For the result of irregular wave test, in case of catenary mooring system, Heave motion affects mooring tension as like the result of regular wave test. When the structure is installed at shallow water, It is essential to get enough foot print radius and to consider of tension response due to heave motion.

(6) For the result of irregular wave with wind test, Both of the mooring systems are influenced by coupled effect of surge and pitch motion attributable to the steady drift and steady heeling of the structure due to wind.

Additional studies on the cylindrical floating vertical axis wind turbines need to identify the generating efficiency of interaction with motion response.

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