Numerical Analysis of the Dynamics of Inter-Linked SPAR structures using Connectors for Possible Wind Farm Application

Hyun-Sung Kim[1,2]
[1]Major in Ship and Ocean Engineering
University of Science and Technology
Daejeon, Korea
[2] Ocean Plant Research Division
Korea Research Institute of Ship and Ocean Engineering
Daejeon, Korea
Email : eegys_zz@kriso.re.kr

Seok Won Hong[1,2], Yun-Ho Kim[2],
Byoung-Wan Kim[1,2] and Sa-Young Hong[1,2]
[1]Major in Ship and Ocean Engineering
University of Science and Technology
Daejeon, Korea
[2]Ocean Plant Research Division
Korea Research Institute of Ship and Ocean Engineering
Daejeon, Korea

***Abstract*—In this paper, the dynamics of multiply inter-linked SPAR structures using connector beams are studied using a commercial numerical code 'OrcaFlex' and the results are compared with experimental results. Multiple SPAR structures are inter-linked by connector beams, and the mooring lines are used only for the outermost SPARs. The basic module is four inter-linked SPAR structures with rhombus (diamond) arrangement. The motion response of each SPAR and loads on the connector beams and mooring lines are studied for the basic module, and the results were agreed well with experimental results.**

Keywords—SPAR, Wind farm, Mooring method, Connector

I. Introduction

The studies on the eco-friendly and renewable energy are increasing due to the growing concerns on the shortage of energy resources and on the pollution problems of fossil fuel. With these needs, the research works on the development of offshore wind farm have been being done very actively.

As the water depth of available offshore area is increasing, the research and development for a floating offshore wind turbine is steadily in progress. The first and well-known example of a floating wind turbine is Hywind OC3 of Statoil in Norway. The supporting structure they adopt was SPAR structure, and joint research works based on Hywind OC3 have been done up to Phase IV (Jonkman, 2010). In addition, other structures such as Semi-submersible, TLP are studied as a support structures for the offshore wind turbine.

Most of studies have been conducted for a single floating structure, however, and the works on the wind farm structures connected each other have been hardly conducted. Thus, KRISO (Korea Research Institute of Ships and Ocean Engineering) have performed basic research on the development of inter-linked wind farm structures with connectors and mooring systems based on SPARs during last 3 years (Hong et al., 2012, Kim et al., 2015).

This study is aimed to investigate the response of the basic SPAR module with advanced mooring method for the development of wind farm using the SPAR structures. Mooring lines are modeled by equivalent linear springs, and connectors are modeled by cylindrical beams. For the basic module of four SPARs, 5 connectors and 10 connection link are used. Four SPAR structures are arranged to a rhombus shape and moored to each mooring line. The front SPAR that faces with incident wave firstly has two mooring lines back and forth. By comparing the numerical values with experimental ones, the motion response of floating structure and structural characteristics of connector are shown and discussed.

II. Model of Study

In this work, Hywind OC3 that is 5MW class offshore wind turbine was used as the basic SPAR structure (Fig. 1). Table I show the properties of this structure.

To simplify the analyses, we adopted a basic module as the four SPAR structures arranged as shown in Fig. 2. Four SPAR structures are linked to each other by using the connectors and moored to each mooring line. The stiffness of the linear mooring spring of SPAR #1 (Kc = 11.036ton/m) is about 7 times stiffener than others that are used to SPAR #2, #3 and #4 (Kc = 1.591 ton/m). The stiffness of the soft mooring spring of SPAR #2, #3 and #4 are the same with that of the original Hywind OC3.

The separation distance between structures is 500m, and connector's length is 494m. Connectors and mooring lines were linked to 70m below the surface of water. We adopted a connection link between SPAR structure and connector to minimize the local stress at the contact point. In case that structure and connector are linked directly, critical stress may be imposed on the connectors by relative motion between them. So, the connection link could allow the first order motion by wave, and mitigate the stress level at the connector. The properties of connection link are determined in pursuance of the preparation

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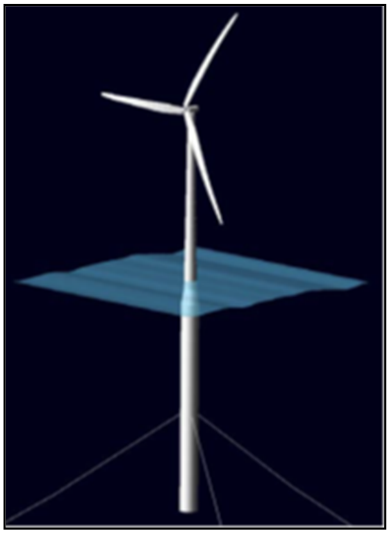
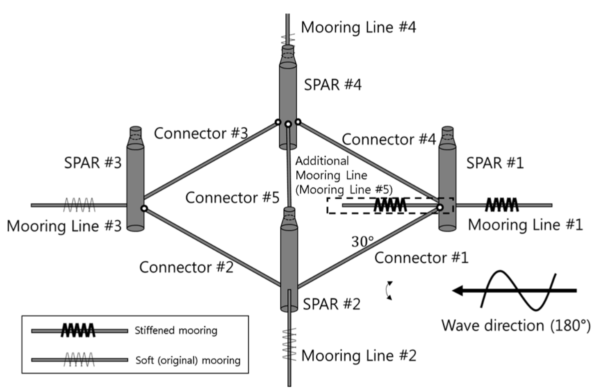
for the experiment. The spring constant of the link has two values for compression (34.14 ton/m) and tension (68.85 ton/m).



Fig, 1. Image of Hywind OC3

TABLE I. PROPERTIES OF HYWIND OC3

Property	Value
Displacement [ton]	8276.0
Draft [m]	120.0
CG form S.W.L. [m]	-80.97
CB form S.W.L. [m]	-60.00
Ixx w.r.t. CG [kg.m^2]	8.49E+10
Iyy w.r.t. CG [kg.m^2]	8.49E+10
Izz w.r.t. CG [kg.m^2]	1.64E+08
GM_L [m]	18.91
A_w [m^2]	32.81
$w_{n,heave}$ [rad/s]	0.20
$w_{n,pitch}$ [rad/s]	0.22



Fig, 2. Arrangement of the basic module with SPAR structures

TABLE II. PROPERTIES OF CONNECTOR

Property	Prototype	Experimental model
Weight in water	0.299 kN/m	15.06 g/m
Axial stiffness	25,454.4 MN	279.33 kN
Bending stiffness	57,639.7MN.m^2	312.36 N.m^2

The connector was modeled as a cylindrical beam, and the properties of the beam are determined by carrying out the parametric studies in the previous work (Kim et al., 2014). In real design, the connector should be truss structure, but it was modeled as a cylindrical pipe in this study to simplify the geometrical modeling work for both numerical and experimental analyses.

Although there were differences in geometries, material properties such as weight in water, axial and bending stiffness should be modeled almost the same as those of prototype. However, axial stiffness of the experimental model is 5 times larger than that of prototype as shown in Table II. The bending characteristic of the connector is dominant, so the comparison of bending stiffness is focused.

A. *Numerical Models*

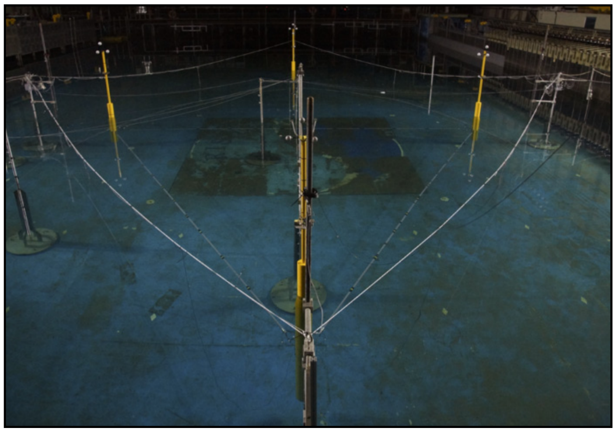
To perform the numerical simulation, the commercial numerical code 'OrcaFlex' was used. In numerical modeling, connector is represented by homogeneous pipe whose properties like as weight in water, bending and axial stiffness are equal to those of the experimental model. And mooring lines is modeled by using the equivalent linear spring and connection link is done by nonlinear spring. The structural properties and characteristics of the SPAR structures were modeled as same as those of Hywind OC3.

B. *Experimental Models*

To realize the model for the experiment, Froude law is applied and the scale ratio is given as 1/45. The properties of Hywind OC3 experimental model are shown to Table III. The detailed information of experimental model is represented to the previous study (Kim et al., 2015). The totally experimental setup is shown to Fig. 3.

TABLE III. PROPERTIES OF EXPERIMENTAL MODEL

Property	Value
Displacement [ton]	0.09
Draft [m]	2.67
CG form S.W.L. [m]	-1.80
CB form S.W.L. [m]	-1.33
Kxx [m]	2.25
Kyy [m]	2.25
Kzz [m]	0.10
A_w [m^2]	0.02
$T_{n,heave}$ [sec]	4.68
$T_{n,pitch}$ [sec]	4.26



Fig, 3. Overall experimental setup of SPAR structures

III. ANALYSIS CONDITIONS

The numerical and experimental analyses for advanced mooring system with inter-linked SPAR structures were performed. Mainly, motion of floating structures and structural responses of beam connectors were evaluated. As previously stated, SPAR #1 has only two mooring lines back and forth, and remnant structures have one line in outward direction respectively. In this way, SPAR #1 would be like to function as a turret. Its property values are presented for Table IV.

Firstly, static pull-out test were performed to verify the characteristic of the beam connector. To model static pull-out test, two SPAR structures and one connector were used. And one structure was fixed and the other was pulled out forcibly. Tension of connector at end point and offset were measured and compared. And, to match the natural period of motion response, free decay test was conducted. For overall structures, SPAR #3 pulled to surge direction and motion of SPAR #1 was measured and compared.

For both numerical and experimental analyses, wave condition was only applied as environmental condition. Regular wave and irregular wave tests were performed and, for regular wave test, wave height was constant for 2m and wave frequencies were ranged from 0.2 rad/s to 0.9 rad/s. For irregular wave test, the operation and 50-year period wave conditions in front sea of Jeju island where structure would be installed. were conducted (Table V). And, wave direction was only 180 degree same as head sea.

TABLE IV. PROPERTIES OF MOORING LINES

Mooring line No.	Stiffness [kN]	Note
Mooring line #1	10826.316	-
Mooring line #2	1560.771	Original Hywind OC3 mooring line
Mooring line #3	1560.771	
Mooring line #4	1560.771	
Mooring line #5	10826.316	Additional line for SPAR #1

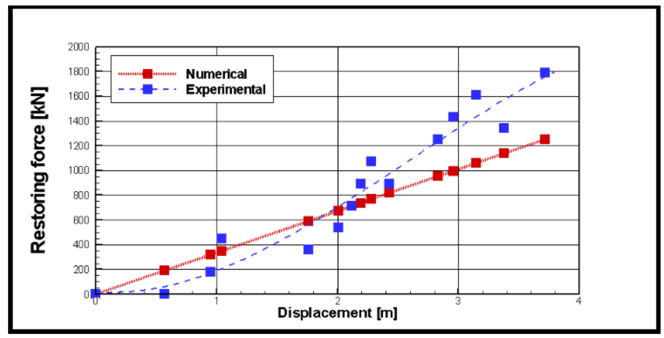
TABLE V. IRREVULAR WAVE CONDITIONS

Condition	Hs [m]	Tp [sec]	Gamma	Note
Operation	2.4	10.0	2.5	
50-yaer period wave	8.0	12.0	2.5	In front sea of Jeju island

IV. RESULTS AND DISCUSSION

A. *Static pull-out test*

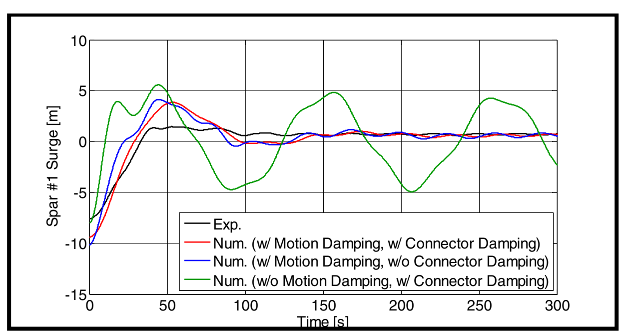
The results on static pull-out test were compared with restoring force according to displacements. As shown in Fig. 4, the numerical and experimental results are correspond at small displacements approximately. As increasing the displacement, a differences are found. Experimental results showed slightly nonlinear and numerical those are perfectly linear. This may be due to difference in elasticity of materials. In numerical model, connector's material is steel, while that in experimental model is plastic. Also, stiffness coefficient of the mechanism is similar to connection link's rather than connector. So, connector's elongation doesn't occur and restoring force is seen to depend on the connection link.



Fig, 4. Result of static pull-out test

B. *Free decay test*

The surge free decay test was performed to match the natural frequency of motion response. Damping effects on motion and connector were applied in several cases. As shown in Fig. 5, the case applying both motion and connector damping was the most similar result with experiment. But there was limit to satisfy the result of experiment exactly. It is considered that numerical model and simulation can't represent an interaction of complex system consisting of multiple inter-linked SPARs, connectors and mooring lines in reality.



Fig, 5. Result of surge free decay test

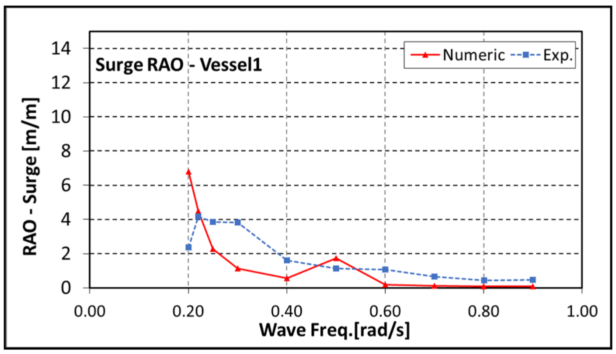
C. *Regular wave test*

1) Motion responses

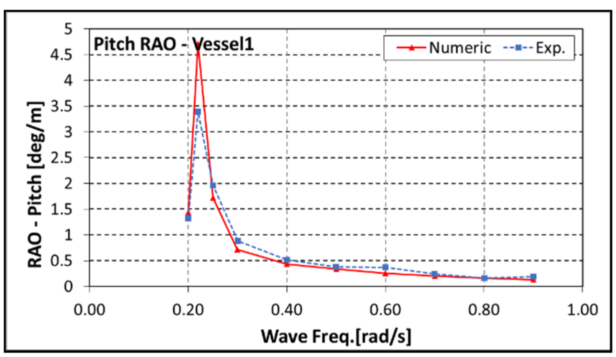
In regular wave test, motion responses of structures are analyzed at center of gravity of SPAR structure. Figs. 6 and 7 show surge and pitch RAOs comparison with experiment of SPAR #1. Most of the numerical results on motion of SPAR structure are mostly met with experimental values.

Vertical motion such as pitch is almost same on numerical and experimental results. Translational motion such as surge is similar with trend but not with wave frequency whose have maximum amplitudes. This is due to disagreement of surge natural frequency.

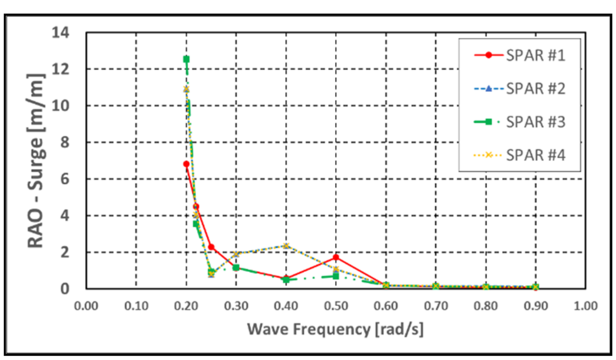
Fig. 8 represents RAO comparison on the surge motion in numerical analysis. Amplitude of SPAR #1 is smaller than those of other SPARs because of large stiffness of mooring spring of SPAR #1. Also, there are difference on frequency which occurs additional resonance.



Fig, 6. Surge RAO of SPAR #1



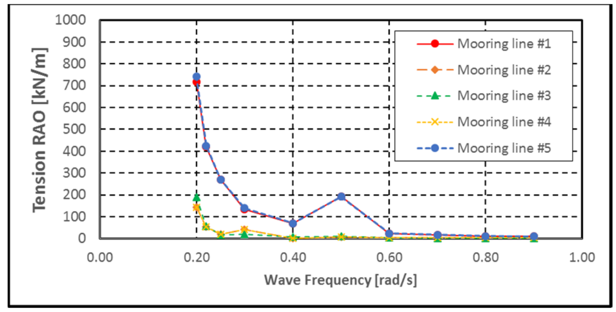
Fig, 7. Pitch RAO of SPAR #1



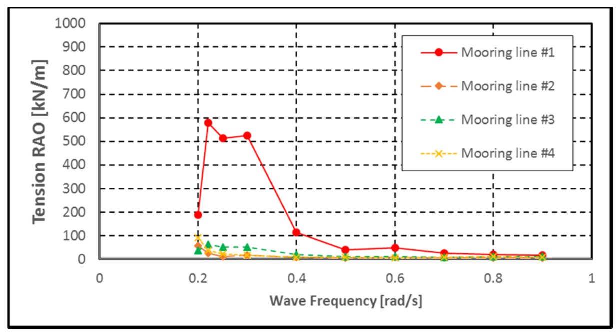
Fig, 8. Surge RAO comparison with SPAR structure

2) Mooring line tension

Mooring line tension RAOs are represented to Figs. 9 and 10 for numerical and experimental analyses respectively. In two cases, tension of mooring line 1 has the largest value due to its mooring stiffness. For numerical analysis, at 0.5 rad/s, there was second resonance response. But, resonance responses occurred at 0,2 ~ 0.3 rad/s for experiment.



Fig, 9. Tension RAO comparison on mooring lines in numerical analysis

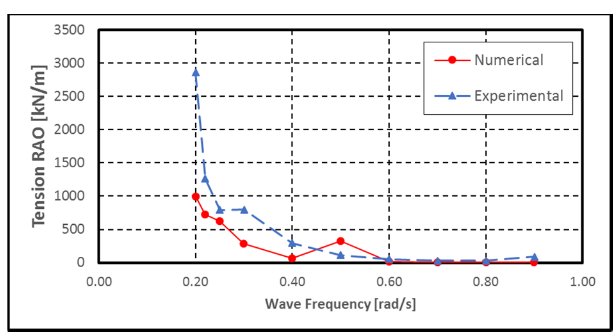


Fig, 10. Tension RAO comparison on mooring lines in experiment

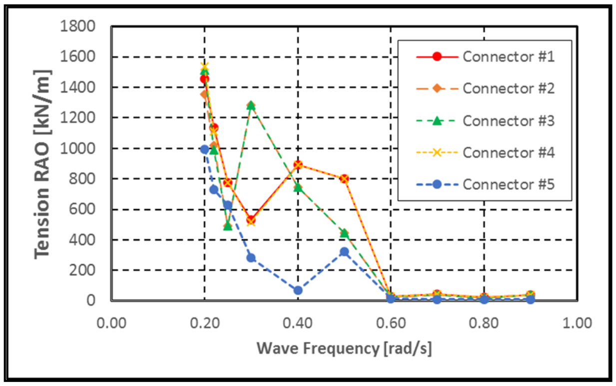
3) Connector end point tension

Connector's effective tension at end point that is connected to connection link has similar trend with experimental values (Fig. 11 for connector #5). But experiment's maximum value is larger than numerical result. It is considered to be due to connection link's effect.

Fig. 12 represents tension RAO comparison on connectors. All of connectors have similar maximum values, but frequencies which second resonance occurs at are distinct, It is considered that the difference of spring stiffness and relative motion of vessel and connector affect resonance responses.



Fig, 11. Tension RAO of connector #5

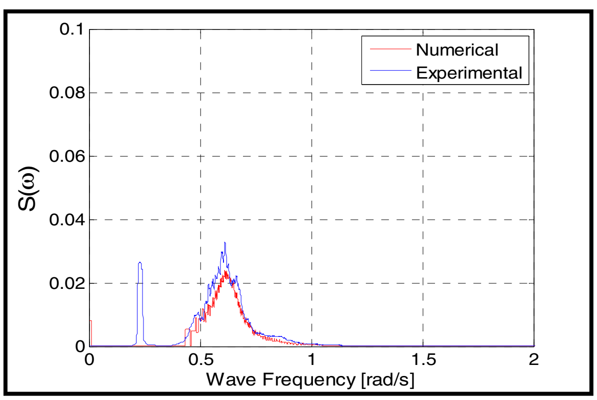


Fig, 12. Tension RAO comparison on connectors

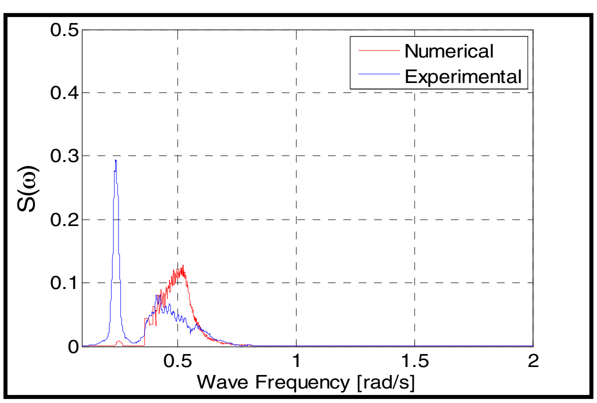
D. *Irregular wave test*

1) Motion response

For irregular wave test, motion response spectra were analyzed and compared. Fig. 13 show pitch response spectrum of SPAR #1 at operation condition and Fig. 14 do heave response spectrum at 50-year period wave in front sea of Jeju island. As shown in figures, spectra are considered to match well with experimental results. But, at the surrounding 0.2 rad/s, there is large amplitude only in experiment. This is thought to be owing to a complicated effect of system that can't be realized in numerical simulation.



Fig, 13. Pitch response spectrum of SPAR #1 at operation condition

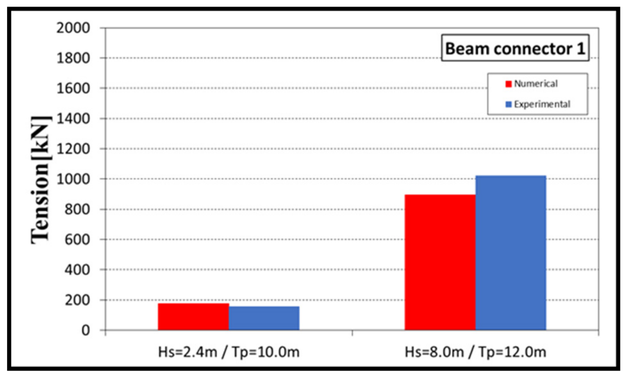


Fig, 14. Heave response spectrum of SPAR #1 at 50-year period condition

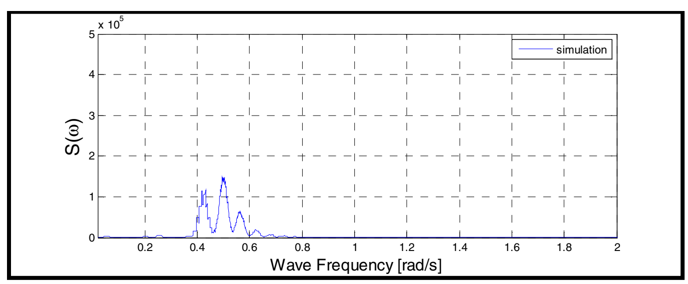
2) Beam connector tension at end point

By using the results of analysis for irregular wave test, connector's structural stability was verified. In Fig. 13, tension SDA (Significant Double Amplitude) of connector #1 are represented for operation and 50-year period wave conditions. Figs. 16 and 17 show tension response spectrum. The responses in two cases occur at similar frequencies, but amplitude in experiment is larger than that of numerical analysis in common with tension SDA results.

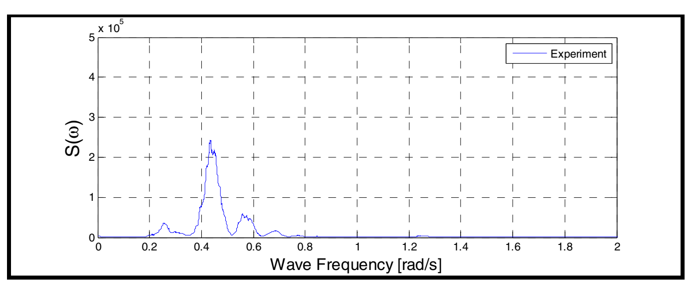
And, in two cases, maximum buckling stresses were calculated and verified for allowable buckling stress. When the connector was designed, allowable stress for buckling is defined to about 225 MPa. For experimental and numerical analyses, maximum stresses range from 40MPa to 65MPa approximately. So, this connector is safe for 50-year period wave condition as well as operation condition.



Fig, 15. Tension SDA of connector #1



Fig, 16. Tension response spectrum of connector #1 in numerical analysis



Fig, 17. Tension response spectrum of connector #1 in experimental analysis

V. CONCLUSIONS

The numerical analysis on dynamics of inter-linked SPAR structures for the development of windfarm was considered in this work. Numerical analysis results were compared with experimental ones. The conclusion drawn from this work are listed as follows :

A. In static pull-out test's results, it is seen that the connection link affect structural characteristics of connector beam.

B. Motion response of SPAR structure matches relatively with experimental results in regular wave test. And mooring line's stiffness influences the motion of structures.

C. Tension loaded on the mooring line and beam connector follow trend line well. Floating structure and connection link have a influence on tension applied to connector.

D. Motion responses in irregular wave test are matched with experimental results, but a complicated and nonlinear effect of overall system could not be realized in this numerical simulation.

E. The connector beam was assessed to be safe enough for operation and 50-year period wave condition in installation site.

From this work, more detailed studies will be needed including the consideration of additional environment condition, rotor dynamics and so on. Also, numerical modeling are need to realize the experimental model more specifically.

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REFERENCES

[1] Hong, SY, SW Hong, BW Nam and TH Kim, "Design and Analysis of an array of Floating Wind Turbine Structure, ISOPE-PACOMES, Vladivostok, 2012.

[2] SW Hong, et al., Parts III and VII of Report 'Study on SPAR Platfrom technology for Multiple Deployment', 2014.

[3] HS Kim, SW Hong, YH Kim, BW Kim and SY Hong. "A Comparative Study on Mooring methods of Advanced Concept Multiple SPAR Structure for the Development of Wind Farm", KAOSTS Joint Conference, May 2015.

[4] YH Kim, JP Hong, YS Kim, HS Kim, SY Hong and SW Hong, "An Experimental Study on the Motion and Structural Characteristics of an Interlinked Spars'Array", ISOPE, Kona, June 2015.

[5] J. Jomkman "Definition of the Floating System for Phase IV of OC3", NREL/TP-500-47535, 2010.

[6] YH Kim, SY Hong, SW Hong and HG Sung, "A Study on the Connectors for Constructing Offshore Wind Farms based on SPAR Platfroms", KOSMEE, Oct. 2014

[7] API-RP 2A-WSD, "Recommended Practice for Planning, Designing and Constructung Fixed Offshore Platform – Working Stress Design", American Petroleum Institute, 2010.

[8] Kim,B.W.,Sung,H.G.,Kim,J.H.,Hong,S.Y., "Comparison of linear spring and nonliear FEM methods in dynamic coupled analysis of floating structure and mooring system", Journal of Fluids and Structures 42, 205-227, 2013.

[9] OrcaFlex Manual version 9.8a, Orcina Ltd., 2014.