Numerical analysis of the coupling response of a semi-submersible platform with its mooring system

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ABSTRACT
Due to highly increasing ocean energy demand, more and more researches focus on the performance of the platform in the aspect of both structure and hydrodynamics. The coupling response of the system combined with the platform and its mooring lines is studied numerically in this paper with the viscous hydrodynamic solver naoe-FOAM-SJTU, which is based on open source codes of OpenFOAM. The influence of numbers of and angles between mooring lines on the platform motion and mooring line fatigue is focused on and several important conclusions are drawn with deep analysis.
KEY WORDS: Coupling system; motion response; mooring line force; naoe-FOAM-SJTU solver.

INTRODUCTION

With more and more attention people paid on ocean and ocean engineering construction, analysis or investigation of the wave impact on the coupling system of platforms and mooring lines, which is necessary for floating structures to resist the motion induced by environmental load, such as current, wind and wave, counts more and gradually becomes the researchful focus. As the computational ability of the processors promote immensely, the Computational Fluid Dynamic (CFD) is going to play a more important role in analysis, design and prediction than past. Using the method of numerical analysis to estimate or predict the condition of the coupling system under wave impact has become the key procedure in floating structure design at the advantages of both high-reliability and low costs.

Md. Ataur Rahman, et al. (2006)[1] investigated a two-dimensional numerical estimation method of calculating dynamics of a pontoon type submerged floating breakwater and forces acting on its mooring lines due to wave action and validated with water surface elevation, dynamic displacement and force acting on mooring lines. Tahar and Kim (2008)[2] adopted rod theory and finite element method (FEM) to take large elongation and nonlinear stress-strain relations into consideration and get the result that inclusion of these elements can increase the stability and reliability of the results in high strain cases. Hall, et al. (2011) [3] studied an OC3-Hywind turbine about the difference between model of FEM and a quasi-static catenary model, and only little difference was found. Diamantoulaki and Angelides (2011) [4] conducted a study about influence of the number of mooring lines on the platform motion response and little influence was found on heave motion. E.Y. Choi, et al. (2015) [5] adopted a simplified 1/75 scale model to predict the dynamic responses of a spar-type floating platform and relative differences between numerical and experimental results at resonance frequency. Yong Ma, et al. (2015) [6] predicted mooring line tension and motion response of vertical axis floating tidal energy converter with ANSYS AQWA software. Wei Peng, et al. (2013) [7] simulated the fully nonlinear interactions between water waves and movable submerged floating breakwater with a 2D numerical estimation method and the results showed good agreement with measurements of the spatio-temporal evolution of the free surface displacement. Shivaji GT and Sen D (2015) [8] developed a coupled time domain solution based on a 3D NWT approach to determine 6 DOF motions of moored floating body with a fully linear and a nonlinear method. Yipeng Pan, Prasanta Kumar Sahoo and Lin Lu (2015) [9] discussed the coupled hydrodynamic response for catenary mooring line of large floating structure (LFS) in deep sea condition and analyzed the influence of dynamic response characteristic and some related parameters of mooring lines (length and angle between lines) and platform to LFS catenary system's motion. To continue on, a research about influence of numbers of and angles between mooring lines will be conducted with several modules in the solver naoe-FOAM-SJTU.

MATHEMATICAL EQUATIONS

The numerical tool, naoe-FOAM-SJTU, used in this paper is based on interDyMFoam, a built-in solver in OpenFOAM which is efficient to solve two incompressible, isothermal immiscible fluids as well as dynamic mesh motion. Meanwhile, several modules are integrated to make the solver more effective in solving the coupling interaction between fluid and structure. Due to the geometrical features and dynamic features of the platform, Laminar Reynolds module is carried out in the calculation. Some important mathematical equations and concept used in these modules are shown as below.

1. Governing equations

Developed from conservation of momentum of fluid, problems related to transient, incompressible and viscous fluid are governed by Navier-Stokes equations.

$$\nabla \cdot U = 0 \tag{1}$$

$$\frac{\partial \rho U}{\partial t} + \nabla\big(\rho\big(U - U_g\big)U\big) = -\nabla p_d - g \cdot x\nabla\rho + \nabla(\mu\nabla U) + f_\sigma \tag{2}$$

Where U and U_g represent velocity of flow field and grid nodes separately; $p_d = p - \rho \cdot g \cdot x$ is dynamic pressure of flow field by subtracting the hydrostatic part from total pressure p ; g, ρ and μ denote the gravity acceleration vector, density and dynamic viscosity of fluid respectively; f_σ is surface tension which only takes effect at the free surface and equals zero elsewhere. The Laminar model means that the Navier-Stokes equation will be solved directly and the turbulence model is not considered in the calculation.

2. Free Surface equations

Volume of Fluid (VOF) method (Hirt and Nichols, 1981) [10] has been adopted in the solver to capture the free surface better. Volume fraction function α represents the ratio of cell volume fluid occupies and follows the below distribution:

$$\begin{cases} \alpha = 0, & air \\ \alpha = 1, & water \\ 0 < \alpha < 1, & free\ surface \end{cases} \tag{3}$$

And the volume fraction function α is also governed by transport equation:

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot [\big(U - U_g\big)\alpha + \nabla \cdot [U_r(1-\alpha)\alpha] = 0 \tag{4}$$

Where $\boldsymbol{U_r}$ is a relative velocity field. For two-phase flow problems, the physical properties of one fluid are calculated as weighted averages based on volume fraction of water and air in one cell as below:

$$\begin{cases} \rho = \alpha\rho_l + (1-\alpha)\rho_g \\ \mu = \alpha\mu_l + (1-\alpha)\mu_g \end{cases} \tag{5}$$

Where subscript l and g represents liquid and gas.

3. Wave generation/damping equations

In the solver, wave is generated by specifying free surface and velocity distribution at inlet boundary according to various wave theories (Baudic, et al., 2001) [11] to effectively avoid the movement of the boundary. Linear theory is adopted in this paper to produce regular waves and free surface can be described as below.

$$\eta = Acos\theta \tag{6}$$

To reduce the reflection of wave and interference of reflected wave and incident wave, a wave damping module takes effect by adding an additional artificial viscous term to the source term of the momentum equation. The new term is expressed as:

$$\mathbf{f}_s = -\rho\mu_s\mathbf{U} \tag{7}$$

Where μ_s is the artificial viscosity calculated by the following equation:

$$\mu_s(x) = \begin{cases} \alpha_s(\frac{x-x_0}{L_s})^2, & x > x_0 \\ 0, & x \le x_0 \end{cases} \tag{8}$$

Where α_s is a dimensionless quantity defining damping strength. Other parameter is shown in the following Fig1. Where x denotes the coordinates in the x direction; x_0, L_s represents the position and length of the sponge layer.

4. Mooring system equations

To calculate the static of mooring lines, a mooring line module based on PEM (Piecewise Extrapolating Method) is developed and integrated into the solver. According to PEM, the mooring line is separated to a number of segments and a typical sample is in the Fig 2. The statics equilibrium equations in horizontal and vertical directions are shown as below:

$$\begin{cases} T_{xi+1} = T_{xi} + F_i ds \cos\varphi_{i+1} + D_i ds \sin\varphi_{i+1} \\ T_{zi+1} + D_i ds \cos\varphi_{i+1} = T_{zi} + F_i\, ds \sin\varphi_{i+1} + w_i dl \end{cases} \tag{9}$$

Where T_x, T_z and φ represent horizontal and vertical components of tension at a cross section of one segment and the angle between tension and T_x; dl and ds are length of the segment before and after elongation respectively; w is net submerged weight of lines per unit length; D and F denote normal and tangential components of drag force acting on the segment which are calculated by Morison's equation.

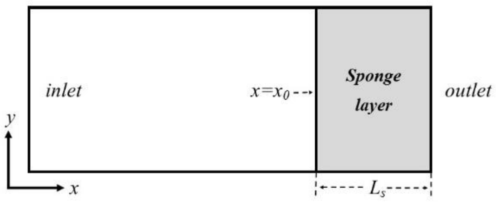

Fig1. Overview of sponge layer

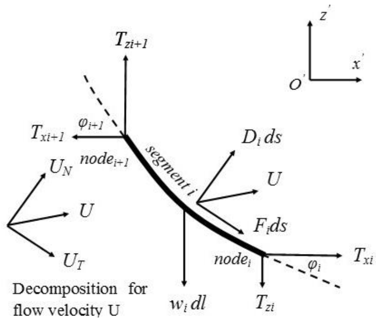

Fig2. Mooring line segment force and coordinates

COMPUTATIONAL MODEL

The computational model in this paper is a DeepCwind semi-submersible platform which has been investigated by Alexandwer (2012) [12] with both experimental and numerical methods FAST. The features and parameters of the platform will be introduced in the section 1, its mooring line system in section 2 and computational domain in section 3.

1. platform

The platform used for this study is a standard model named OC4 from National Renewable Energy Laboratory (NREL) and has been investigated widely in the world by a lot of researchers. The platform is composed of three offset vertical columns with a larger diameter base at the bottom, one central smaller column to satisfy the requirement of stability and some horizontal or diagonal bracings. Some simplification is also conducted to make the calculation more fluent and reduce the processing time, especially for some unimportant diagonal cross bracings. The primary parameters of the OC4 platform is listed in the Table 1. A whole model and its coordinate system is shown in the Fig3 and Fig4 respectively.

Table1. Platform gross properties

Primary parameter	Value
Depth of platform base below SWL (total draft)	20m
Elevation of main column (tower base) above SWL	10m
Elevation of offset columns above SWL	12m
Spacing between offset columns	50m
Length of upper columns	16m
Length of case columns	6m
Depth to top of base columns below SWL	14m
Diameter of central column	6.5m
Diameter of offset (upper) columns	12m
Diameter of base columns	24m
Diameter of pontoons and cross braces	1.6m
Displacement	13986.8m^3
Center of mass location below SWL along platform center line	9.936m

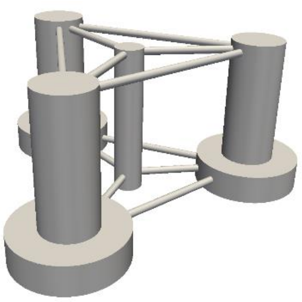
Fig3. Model whole view

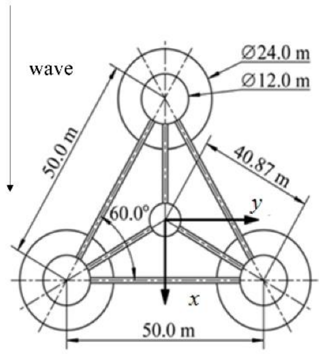

Fig4. Coordinate system

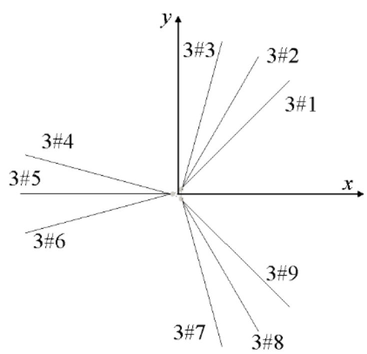

Fig5. Serial number of mooring line

2. Mooring system configuration

A fairlead point is the end point of the mooring line on the platform linking platform and its mooring line. Thus we can continue to define a mooring line group, briefly called group in the following, as a number of mooring lines sharing the same fairlead point and with the same angles between lines in a group. In this paper, we are going to investigate the influence of number of and the angle between the mooring lines in a group on the platform motion and mooring line force.

No matter what the number of mooring lines in a group or angles between mooring lines, other features of each mooring lines are all the same and they are listed in the Table3. Here, we are going to define a new parameter called Whole Angle (WA), which means the total angle between the first mooring line and the last mooring line in a mooring line group.

Table2. mooring line arrangement in this paper

Situation	Number of mooring lines in a group	Whole angle in a group
1	1	0
2	2	10
3	2	20
4	2	30
5	3	10
6	3	20
7	3	30

Table3. Primary parameters of the mooring system

Primary parameter	Value
Number of mooring line group	3
Angles between groups	120°
Depth to anchors below SWL (water depth)	200m
Depth to fairleads below SWL	14m
Radius to fairleads from platform centerline	4.0868m
Radius to anchors from platform centerline	837.6
Equivalent mooring line mass in water	108.63kg/m
Equivalent mooring line extensional stiffness	7.536E+8N

Some other definition is also made in this section. The first one is the name system that we use in this paper. *x*MyA means x mooring lines per group with whole angle of y degree. The second one is the serial number of mooring line. The #1 line is the first mooring line rotating counterclockwise from x axis, and sometimes the number before # means the number of mooring lines in a group, just like Fig5.

3. Computational domain

OpenFOAM is a very complex calculation system with a powerful tool, but quite easy, named snappyHexMesh (OpenFOAM, 2013) [13], to create mesh of high quality with great efficiency. A qualified mesh with about 1.6 million cells is produced by snappyHexMesh with a computational domain $L900m \times B400m \times H300m$. The platform is 300m behind the wave inlet surface and initial free surface is 200m above the bottom of the domain. The overview of the domain is in the Fig6 as well as refinement region near free surface and platform in Fig7.

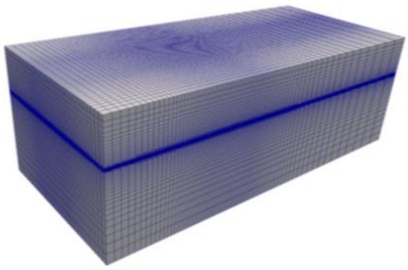

Fig6. Overview of computational domain

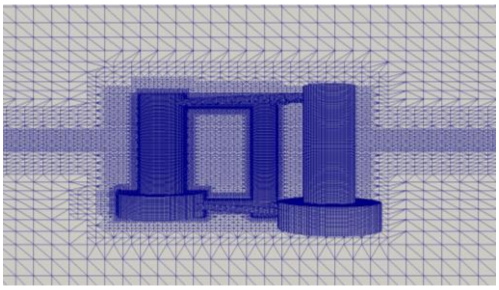

Fig7. Refinement region near free surface and platform

VALIDATION

This paper is based on naoe-FOAM-SJTU solver developed to study problems of hydrodynamics and offshore engineering in various conditions. To validate the availability and effectiveness of the solver, some basic numerical analyses about the motion response under regular waves have been conducted and compared with the experimental results given out by Alexander, et al., 2013 [12]. Five regular waves are carried out due to the experimental results and the models are all the original models with only one mooring line in a group. The main focus of our validation is on the motion response of the coupling system, which can be reflected by response amplitude operators (RAOs) magnitudes. In the meantime of calculating motion response, wave elevation is also recorded with the wave probes in the computational domain to validate the wave condition is correct. As the calculation is only in 3 DoFs (Surge, Heave, Pitch) to reduce the time of calculation and uncertainty, there will be four main outputs in the validation period including the wave condition. The five wave conditions are listed in the Table4 below.

Table4. Wave condition for validation

Amplitude (m)	Periods (s)
3.79	12.1
3.57	14.3
3.79	20
5.15	12.1
5.37	14.3

The RAOs results are shown in the Fig8, Fig9 and Fig10 for surge, heave and pitch respectively. As the results show, the results are better than that from FAST and the solver is validated correctly for calculating the problems related to platform OC4.

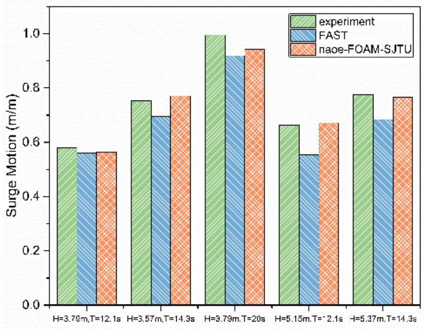

Fig8. Surge motion for validation

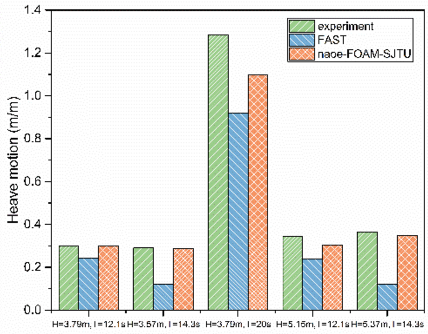

Fig9. Heave motion for validation

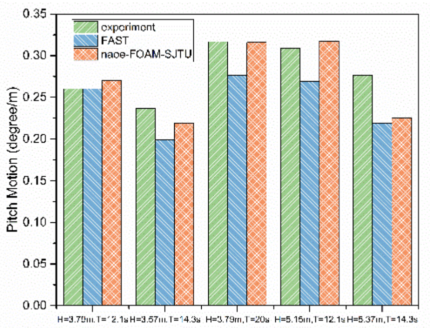

Fig10. Pitch motion for validation

RESULT

To investigate the mooring line influence on the platform, two main factors, the number of and angle between mooring lines in a group, are investigated according to several numerical cases. In this part, all the cases are in the same wave condition as control variables with 5.15m wave height and 12.1s wave period for better investigation. The wave elevation simulated varying with time is shown in the Fig11. Meanwhile, all the cases are calculated to 500s to meet the requirement of International Towing Tank Conference (ITTC) that motion data should be collected at least for 10 quasi-steady cycles under regular wave conditions to ensure accuracy of results (ITTC, 2002) [14]. As the wave height in all the cases are 5.15m, then we can only compare the motion amplitude instead of RAOs.

1. different angles

When there are two mooring lines in a group, pitch, surge and heave motion under different angles are taken into consideration, but the motion response with different angles are quite similar. But this difference can still be told when calculated precisely due to the data given by the solver and we can get Table5. Then we can draw the trend that larger angle between lines corresponds to smaller heave and pitch response, but the difference is so small and it may be due to various factors. Surge motion response is very desultory and no such monotone trend can be drawn.

The force of mooring lines offered is also investigated. This time, a large difference can be obtained due to the result. As for the #1 mooring line, computational time is 500s and it is difficult to have a clear look, so a partial enlarged figure from 400s to 500s is shown in the Fig12. A conclusion can be drawn that when the angle begins to increase, the force on the mooring lines is increasing, which can be explained by that a larger angle will make the mooring line force be larger to provide with the same force in the angular bisector directions, that is useful to make the platform stable. Other mooring lines also follow the same trend.

When there are 3 mooring lines in a group, the motion response and mooring line forces follow the same trend that the angle will not impact motion greatly, but a larger angle will represents a smaller pitch and heave amplitude. As for the force, it is also similar with the 2-line condition result, that larger angle will increase the mooring line force to provide with the same restoring force, which is not economical and may cause severe accidents once mooring line cracks.

Table5. Motion response in different cases

	1M	2M10A	2M20A	2M30A	3M10A	3M20A	3M30A
Surge(m)	3.6991	3.6282	3.5525	3.5701	3.6694	3.5979	3.6881
Heave(m)	1.4694	1.4507	1.4444	1.4328	1.4507	1.4426	1.4314
Pitch(degree)	1.5684	1.4999	1.4838	1.4836	1.3879	1.3861	1.3493

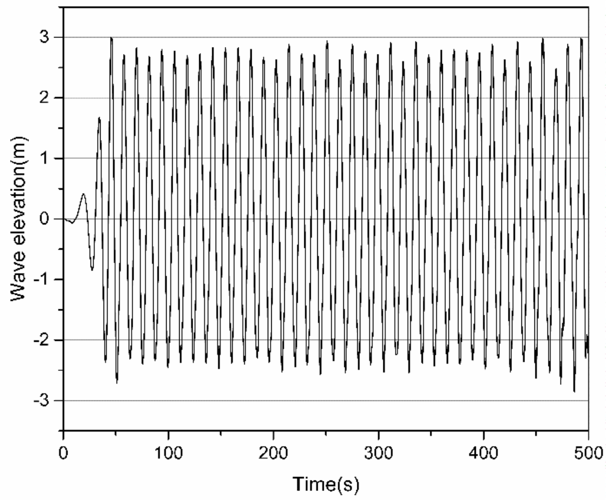

Fig11. Wave elevation

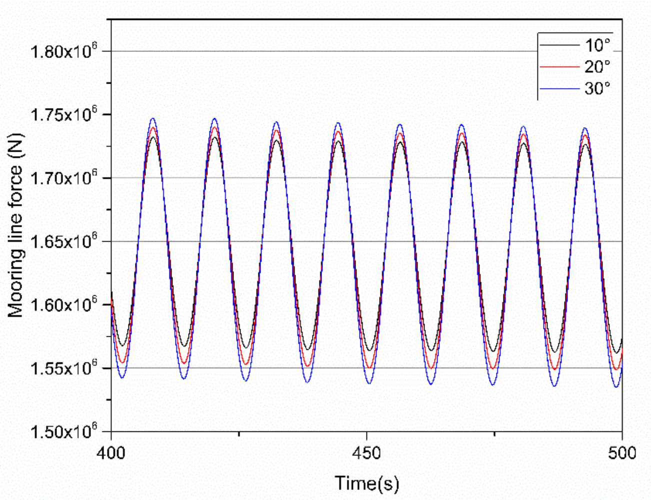

Fig12. From 400s to500s of 2#1 mooring line force

2. Number of mooring lines in a group

In the second section, we will discuss the influence of quantity of mooring lines in a group to the motion response and mooring line force with same WA of 30 degree. Then the model compared in this section will be 1M, 2M30A and 3M30A. In these cases, the motion of pitch and heave are already steady with regular vibration. However, the motion of surge shows two motion patterns when calculating to 2000 seconds, the first one is vibration about its mean value as shown in Fig13, and another one is the vibration of mean value with a quite large period. The mooring line force also shows these patterns and in this study we only focus on the first vibration pattern, thus the calculation time can be not that much and determined to be 500s. All the value are calculated in 20 periods. The motion response of surge, heave and pitch respect to time is shown in the Fig13, Fig14 and Fig15. And the free surface is shown in the Fig16.

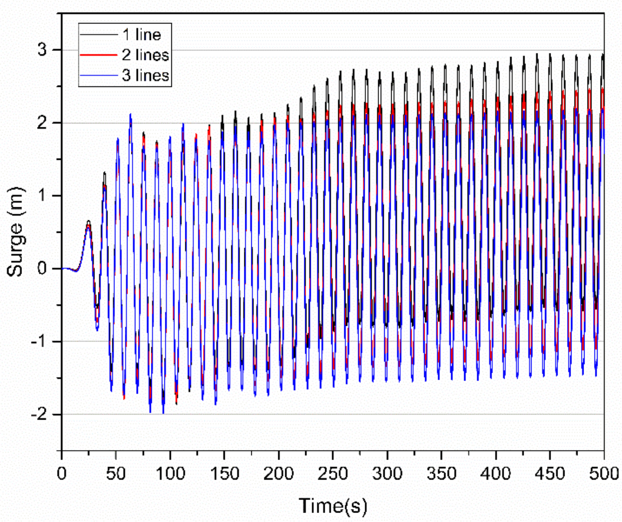

Fig13. Surge response respect to number of mooring lines

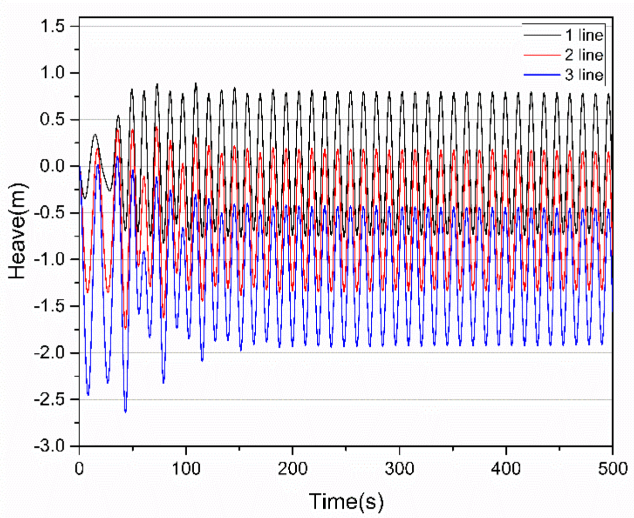

Fig14. Heave response respect to number of mooring lines

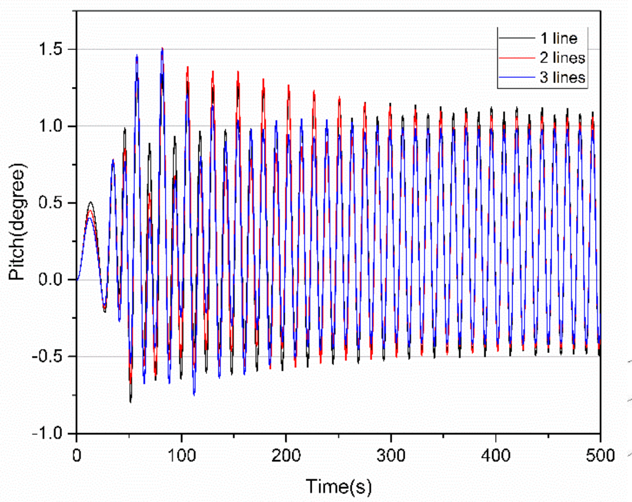

Fig15. Pitch response respect to number of mooring lines

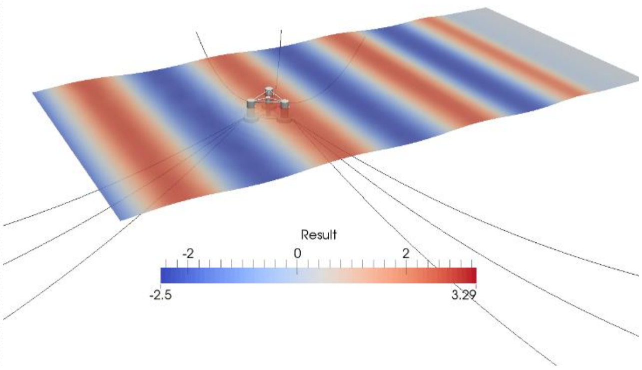

Fig16. Free surface with wave

As the number of mooring lines in a group is different, it is useless to compare the individual mooring line force respect to time in different cases, so the mean force of the mooring lines from a group is analyzed as shown in Fig16, Fig17 and Fig18.

In the steady period of the platform motion, from 300s to 500s, the surge, heave and pitch motion amplitude of 1M is largest, then 2M and that of 3M is smallest. Mean value of heave motion decreases with the increasing of mooring lines greatly because more mooring lines will also bring much larger pre-force on the platform. In the whole progress or the period wave just comes, more lines in a group cause a much more steady motion, which is very practical when we analyze the motion response of a platform under solitary wave or real sea condition where wave changes every time. When it comes to the mean mooring line forces in a group, although the force vibration amplitude does not change dramatically, more lines in a group make mean force vibration amplitude in the whole process becomes smaller, which can explain the reason of steadier motion response. Force on the three mooring lines in the first group of 3M is also investigated that the force vibration amplitude of 3#3 is much larger than that of 3#2, and that of 3#1 is the least, which is due to different elongation in the case of same motion response according to the angles between mooring lines and motion directions.

Thus, in the design phase, if the fact permits, more mooring lines in a group can make the mooring line force and motion response more steady, which is quite beneficial for improvement of production or living standard. But due to much more pre-force on the mooring lines, to provide with same function of the platform, its displacement should be adjusted to make mean heave motion the same.

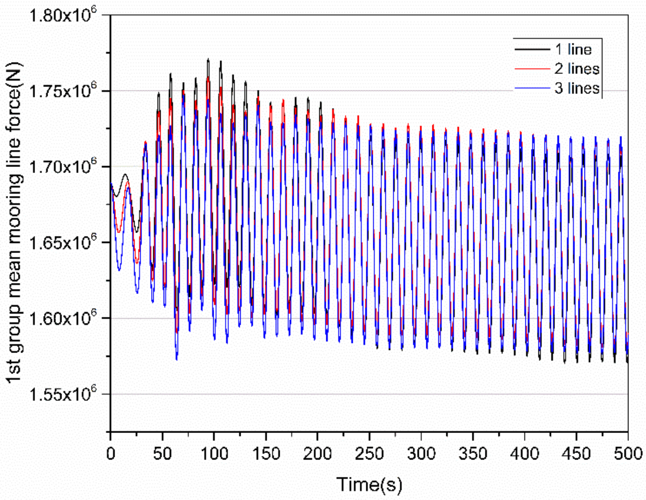

Fig17. First mean force respect to number of mooring lines

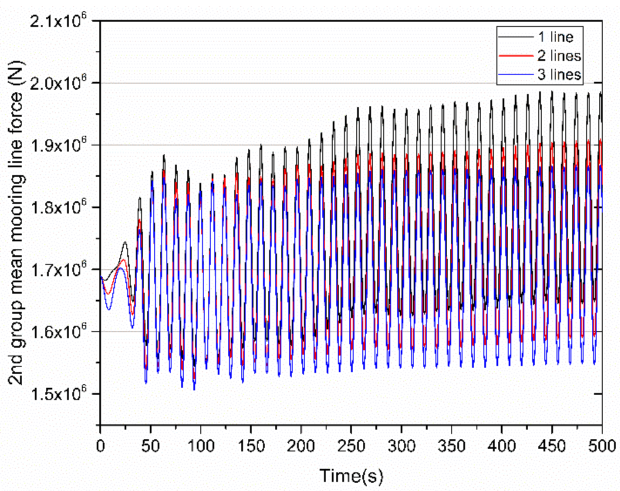

Fig18. Second mean force respect to number of mooring lines

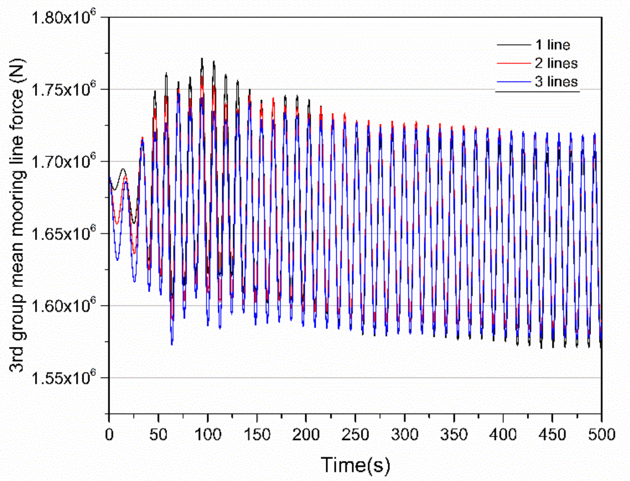

Fig19. Third mean force respect to number of mooring lines

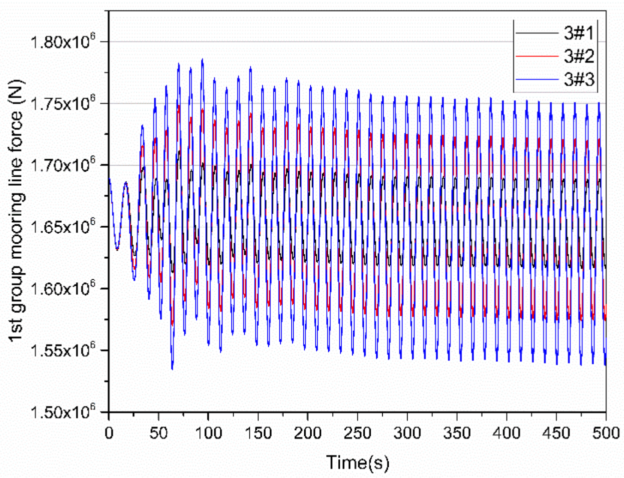

Fig20. Mooring line force in group1

CONCLUSIONS

In this paper, an OC4 wind turbine platform is investigated respect to number of and angles between mooring lines in a group. As the result shows, the angles between mooring lines will not influence the motion response greatly, but the motion response of pitch and heave slightly decrease as the angles increase because the mooring lines can provide restoring force in various directions. But the angle has a great impact on the mooring line force, as a bigger angle corresponds to larger force. As for the number of the mooring lines, the more mooring lines in a group corresponds to less pitch and heave motion response, especially the amplitude of pitch motion. In the meantime, more mooring lines make the force vibration steadier. Thus, more mooring lines are beneficial to reduce mooring line fatigue and enhance the production and living efficiency.

The analysis in this paper is of great practical utility in the future analysis period. If high standard for stability is come up with, then more mooring lines with large angles in a group should be adopted. But if economic aspects are to be highly considered, arranging less mooring lines is a better plan.

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