Decoupling Modeling and Stability Optimization of Multiple Degrees of Freedom Motion Equation of Moored Floating Body

Jiangfeng Zhu (✉ z6j2f8@163.com)

China University of Petroleum, East China

Yuguang Cao

China University of Petroleum, East China

Lei Zhang

China University of Petroleum, East China

Research Article

Keywords: decoupling equation, six degrees of freedom, hydrodynamic stability, motion equation, ocean engineering

Posted Date: October 25th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-992727/v1>

License: This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Decoupling modeling and stability optimization of multiple degrees of freedom motion equation of moored floating body

Jiangfeng Zhu *, Yuguang Cao, Lei Zhang

(Engineering Mechanics Department, College of Pipeline and Civil Engineering, China University of Petroleum (East China), Shandong Key Laboratory of Oil & Gas Storage and Transportation Safety, Qingdao, Shandong 266580)

Abstract: The motion equation and mechanical characteristics of moored floating body are important research directions of offshore floating structures. Aiming at the difference of response law and mechanical change of floating body in different degrees of freedom, the motion and mechanical balance equations of multiple degree of freedom mooring floating body are established based on decoupling analysis method. Combined with the mechanical simulation model, the time-domain motion variation law and the corresponding relationship of the external force of the mooring floating body in the six degrees of freedom of surge, sway, heave, roll, pitch and yaw are analyzed in detail. The paper focuses on the influence of mooring force on the motion and stability of the floating body, and provides a theoretical reference for the dynamic research of offshore mooring floating structure. In addition, based on the six degree of freedom equations and simulation results, combined with the motion response law of traditional tension type and catenary type mooring schemes, two-points and four-points mooring optimization schemes are proposed. Through simulation and comparison, the superiority of two-points and four-points mooring schemes in motion response and mechanical performance of multiple degree of freedom floating body is verified, which provides important theoretical basis and support for the research of time-domain variation law of mooring system and marine safety control.

Key words: decoupling equation; six degrees of freedom; hydrodynamic stability; motion equation; ocean engineering

0 Introduction

Mooring system is an important factor affecting the stability and safe operation of offshore floating body. In recent years, with the development of marine engineering technology, more and more attention has been paid to the hydrodynamic response characteristics of moored floating body. In the traditional research, the hydrodynamic equations of floating body are mostly single. It mainly analyzes the overall motion and the balance of all external loads, but does not specifically analyze the influence of each load on the six degrees of freedom sway motion. Shashikal used the finite element method to analyze the three dimensional interaction between a single

mooring floating structure and waves, and summarized the characteristics of mooring points and cables according to the motion response of the floating body ^[1]; Rahman stated in the research report that the force on the mooring line should be fully considered in the design and motion analysis of floating structure, and the dynamic analysis also includes the motion response of the floating body and mooring tension. Natarajan and Ganapathy ^[3] studied how to calculate the appropriate length and number of mooring lines for the given floating structure and environmental load conditions. They derived the static equilibrium equation of mooring line and developed the computer program of mooring system. Kat and Wichers analyzed the influence of wind, wave and current on the dynamic behavior of a single point mooring ship by establishing a numerical model ^[4]. Ormberg and Larsen pointed out that the full degree of freedom response analysis of moored floating structure is the basis for studying the dynamic response of moored floating body, and the stability of mooring system is studied. However, they did not address mooring stability changes due to changes in specific marine data ^[5]. Barrera et al. studied the dynamic behavior of catenary and tension mooring with the change of structural length ^[6]. Mavrakos and Chatjigeorgiou ^[7] studied the relationship between tension and motion of moored floating body in time domain, and gave the static mooring line equilibrium equation considering gravity and elongation, but they did not specifically study the motion response and mechanical change law of mooring floating body in various degrees of freedom.

Due to the difference of motion response and stability of floating body at sea, the influence of mooring load and Environmental force on each degree of freedom is also different. Therefore, the establishment of multiple degree of freedom hydrodynamic equation of moored floating body is the key to study the stability of floating body under mooring condition. At the same time, it provides a theoretical basis for the in-depth study of the influence of Mooring Load and wind wave current environmental load on the dynamic response of floating body, and provides support for further optimization of mooring scheme and improvement of safety and stability of offshore floating equipment.

1 Establishment of multiple degree of freedom motion equation of floating body

The forces of mooring floating body mainly include marine Environment force F_E , Mooring force F_M , Buoyancy F_B , Gravity F_G . In the traditional research, the influence of external force, moment and motion of floating body is considered comprehensively to establish the equation as follows:

$$m \frac{dV}{dt} = F_E + F_M + F_B + F_G \quad (1)$$

$$I \frac{d\omega}{dt} = T_E + T_M + T_{BG} \quad (2)$$

$$F_M(l) = k_1 l + k_3 l^3 \quad (3)$$

In formula (1) and (2), m , I , V and ω respectively represent the mass, moment of inertia, linear velocity and angular velocity of floating structure; T_E , T_M and T_{BG} are respectively the environmental moment, mooring moment and gravity buoyancy inclination angle action moment. The two formulas mainly establish the influence relationship between force and moment on the motion of floating body, and do not specifically analyze the motion characteristics and force law of floating body in the direction of six degrees of freedom. Equation (3) represents the relationship between mooring force of floating system and elongation l of mooring line, and K_1 and K_3 represent elastic coefficient of mooring line. In order to better analyze the influence of various forces on the 6-DOF motion stability of the floating body, the motion coordinate system of the floating body is established by comprehensively considering the environmental force of wind, wave and current, mooring force, gravity and buoyancy, as shown in figure 1.

Figure 1 motion coordinate system of moored floating body

The influence characteristics of various forces of the floating body on motion are comprehensively shown. Buoyancy F_B and gravity F_G are in the vertical direction, which mainly affect the vertical movement of the floating body (z-axis direction). The environmental force of wind and wave flow F_E is a simple harmonic variation law, which is simplified into horizontal and vertical directions considering the influence of main factors. The mooring force F_M extends from the surface of the sea to the bottom of the sea in an inclined direction. In order to specifically analyze the influence law of each force on the 6-DOF force motion of the floating body, based on the characteristics of the floating body's oscillation around the coordinate axis, taking the flow direction of 0° wind wave (positive direction of X-axis as an example, the relationship between the forces (moments) of the 6-DOF motion is established, as shown in figure 2.

Figure 2 Force (moment) relationship of 6-DOF motion

The relationship between 6-DOF force motion of the floating body and the force (moment) is analyzed in detail in Figure 1-2: (1) Surge (x) direction, the floating body is mainly affected by the x-component force of wind, wave and flow F_{EX} and the X-component force of mooring F_{MX} , because of F_{EX} simple harmonic change rule, at this point, the x surge equation on the right side of resultant force value $F_{EX} + F_{MX2} - F_{MX1}$ is in dynamic change, changes the left floating body movement speed V_x and displacement equation, the large longitudinal oscillation amplitude. (2) Sway (y) direction, the y-direction component force of wind, wave and flow F_{EY} is close to 0. The floating body is mainly affected by the mooring force F_{MY} . Due to the symmetrical arrangement of mooring cables, F_{MY1} and F_{MY2} approximate equilibrium forces, the motion velocity and displacement of the floating body on the left side of the y-sway equation change little, and the amplitude of y-sway can be ignored. (3) In the direction of Heave(z), the floating body is simultaneously affected by the z-component forces of wind, wave and flow, the z-component forces of mooring, buoyancy and gravity. (4) In the direction of Pitch(rx), the restoring torque T_{GBY} under the action of gravity and buoyancy ensures the steady state of the floating body, which is mainly related to the self-stability of the floating body. (5) In the direction of Roll (ry), the pitching Angle of the floating body is generated by the rotation torque T_{EMY} under the action of wind, wave and flow forces and mooring forces. The restoring torque T_{GBY} under the action of gravity and buoyancy restores the balanced position of the floating body. The two torques work together to control the state of a floating body at an Angle of tilt. (6) In the direction of bow Rock (rz) direction, under the action of gravity and buoyancy as the restoring torque T_{GBY} to ensure the floating body steady state.

According to the above analysis of the relationship between the six degrees of

freedom motion of the floating body and the force (moment), based on the decoupling analysis method and on the basis of the traditional motion equation of the floating body, the decoupling model of the six degrees of freedom motion equation of the floating body in the mooring state was established:

$$\left\{ \begin{array}{l} x \quad m \frac{dV_x}{dt} = F_{EX} + F_{MX} \\ y \quad m \frac{dV_y}{dt} = F_{MY} \\ z \quad m \frac{dV_z}{dt} = F_{EZ} + F_{MZ} + F_B + F_G \end{array} \right. \quad (4)$$

$$\left\{ \begin{array}{l} rx \quad I_{xx} \frac{d\omega_{rx}}{dt} = F_{Myz} l_{M\theta x} + F_{BGyz} l_{BG\theta x} \\ ry \quad I_{yy} \frac{d\omega_{ry}}{dt} = F_{Mxz} l_{M\theta y} + F_{Exz} l_{\theta y} + F_{BGxz} l_{BG\theta y} \\ rz \quad I_{zz} \frac{d\omega_{rz}}{dt} = F_{Mxy} l_{M\theta x} \end{array} \right. \quad (5)$$

Formula (4) and (5) establish a mooring floating body force (torque) in relation to the equation of movement of the six degrees of freedom, by decoupling equation expressing form, floating body in various degrees of freedom motion response force (torque) effect is different, mooring force affects surge, sway, heave movement, wind flow force mainly affects surge and heaving response, only has the function of heaving motion of buoyancy and gravity. However, in actual conditions, the magnitude and direction of the environmental force, buoyancy and gravity of wind and wave flow basically remain unchanged, so the motion state and stability of the floating body are changed mainly by controlling the mooring force.

2 The simulation analysis

(1) Model establishment

According to China's yellow sea offshore S4 waters and the depth of the water environmental load parameters, based on the traditional hexagon catenary mooring and tensioning mooring mechanics simulation model is set up, by time domain hydrodynamic simulation of verifying the rationality of mooring condition six degrees of freedom motion equation, at the same time analysis of mooring tension force, wind

flow and mooring six degrees of freedom corresponding influence relations. Table 1 shows the parameters of floating body and mooring rope.

Table 1 Parameters of floating body and mooring line

Mooring project	Parameter
Diameter 、 Height 、 Thickness (m)	20×20×0.3
Waterline (m)	10
Floating mass (kg)	150000kg
Number of mooring lines	6
Length of single catenary cable (m)	150
Length of single tension cable (m)	132
Mass per unit length of cable in water (kg/m)	150
Design water depth (m)	100

The tensioned and catenary mooring buoy models were established. The mass of the floating body was 150000kg, the depth of waterline was 10m, the center of gravity was low and stable, and the number of mooring cables was 6, among which the single catenary cable length was 150m and the single tensioned cable length was 132m. Definition of sea state environment: wave height is 3.6m, period is 8.6s, wind speed is 10.8m/s, sea water velocity is 0.3m/s, wave spectrum is JONSWAP spectrum, wind spectrum is NPD spectrum, load direction is 0°, along the positive direction of X-axis, wind and wave flow are in the same direction. Figure 3 shows the tensioning and catenary mooring floating body models.

Figure 3 Two mooring floating body models

The model accuracy was verified by attenuation test of the mooring buoy. CFD model (flow-3D) and PF model (PWT) were considered to be compared. The CFD model contains two NWTs. The combined model uses A smaller (NWT A) (which does not include any incident waves), while A larger (NWT B) (which can generate waves) is used to compare the differences in the results of the four models of A BUOY. Figure 4 attenuation test comparison results are obtained, which can meet the accurate requirements in the refining area.

Figure 4 comparison results of attenuation test

Considering the symmetry of the floating body, the wave direction is chosen to be $0^{\circ} \sim 180^{\circ}$ with 30° intervals. The natural period of OC4 on three degrees of freedom, including heave, roll and pitch, was compared with the experimental results. As shown in table 2, the error was not more than 3%, which verified the accuracy of the model.

Table 2 natural period of floating body			
Natural period/s	Heave	Rolling	Pitch
Simulation	16.02	25.54	25.54
Test	16.5	25.96	25.8
Error	2.9%	1.6%	1.0%

(2) Six-degree-of-freedom motion simulation analysis of two mooring modes

The six-degree-of-freedom motion simulation analysis of tensioned and catenary mooring floats was carried out to explore the variation law of motion of two different mooring modes in the direction of six-degree-of-freedom and the

characteristics of the influence of mooring tension. Wind and wave flow environment force is set as 0° direction. Figure 4 and 5 show the time-domain simulation results of the six degrees of freedom motion of two kinds of mooring floats.

(a) 3-DOF drift variation of tension type (b) 3-DOF drift variation of catenary type

Figure 5 Drift variation law of mooring floating body with three degrees of freedom

Figure 5 shows the three-degree-of-freedom (DOF) fluctuation variation law of the mooring buoy. According to Figure 4 (a), the motion variation law of the tensioned mooring buoy in the three DOF directions of longitudinal, transverse and vertical is relatively stable, and the motion amplitude is between $\pm 2\text{m}$. Among them, the initial motion amplitude in the longitudinal direction is large and then becomes gradually stable. At the beginning of the simulation, the amplitude of the motion of the yaw direction is small, but increases gradually with the time domain change and tends to be stable. The direction of heave is mainly controlled by buoyancy and gravity. The values of the two forces are large and change steadily. Therefore, the amplitude of the motion response in the direction of heave is small and relatively stable in the whole time domain simulation process.

It can be seen from Figure 5 (b) that the variation rules of the catenary mooring floating body in the directions of surge, surge and heave are quite different. Due to the

mooring freedom of catenary cables, the motion displacement of the floating body increases rapidly to the maximum under the action of wind, wave and flow environmental forces in the longitudinal direction, and then the motion of the floating body gradually tends to be stable under the joint action of the mooring force and wind, wave and flow environmental forces. The amplitude of motion response in the direction of oscillation is close to 0, and the force is balanced and stable. The direction of heave is similar to that of tensioned mooring, but the motion amplitude is slightly larger than that of tensioned floating body due to the influence of mooring rope length.

Figure 6 Variation Law of 3-DOF sway angle of moored floating body

Figure 6 shows the variation law of the three-degree-of-freedom rotation Angle of the mooring buoy. According to Figure 6 (c), the variation amplitude of the three-degree-of-freedom rotation Angle of the tensioned mooring buoy in the directions of roll, pitch and bow is relatively close, and the motion amplitude is between $\pm 4.5^\circ$. Among them, the initial motion amplitude of pitch direction is large, and then gradually becomes stable, which is similar to the change rule of surge. At the beginning of the simulation, the motion amplitudes of roll and bow roll

direction are small, and gradually increase and become stable with the change of time domain, which is similar to the change of sway.

From figure 6 (d), catenary mooring floating body in roll, pitch, and bow wave direction of three degrees of freedom movement are relatively stable, the transverse wave and stem the entire time domain response close to 0, pitch started mainly by wind circulation torque effect produce larger Angle, the moved with the floating and mooring tension increases, reply torque increases gradually, floating body pitching response gradually stable.

(a) X-direction tension mooring force

(b) X-direction catenary mooring force

(c) Y-direction tension mooring force

(d) Y-direction catenary mooring force

(e) Z-direction tension mooring force

(f) Z-direction catenary mooring force

Figure 7 Variation Law of two mooring tensions

The variation law of each cable tension under two mooring modes is analyzed. As shown in figure 7 (a), (c) and (e), in the tensioned mooring floating body, the impact of the mooring cables changes significantly, and the amplitude changes greatly. This is mainly due to the larger binding force of the mooring cables, and the relatively small displacement of the floating body causes a large change in the amplitude of the mooring tension. In the X, Y, Z three, mooring main cable tensioning type (1), (2), (3) number of cable tension of mooring amplitude is bigger, in the time domain analysis in the process of changing trends are basically the same, no. 4, 5, 6 cable tension of mooring amplitude is small, at the beginning of the strain amplitude close to zero, as the simulation time increases, the mooring tension increases gradually, and figure 5 (a) drifting tension type three degrees of freedom change law is similar; The variation law of the six cables in X, Y and Z is close.

Different from the tensioned mooring floating body, the tension of catenary mooring presents a simple harmonic attenuation change in the three directions of X, Y and Z, as shown in figure 7 (b), (d) and (f). The change of the overall harmonic attenuation of the mooring tension is similar to the change law of three-degree-of-freedom dangling in the catenary figure 5 (b). Due to the symmetry of the arrangement of the six cables, the wind and wave flow is in the direction of 0° . In the X and Y directions, the mooring tension of, and cables is symmetrical, and the mechanical effect is nearly balanced. As the arrangement of and cables is consistent

with the trend of wind and wave flow, and the tension of cables is near the wind direction, the variation law of tension is closer to the response characteristics of floating body's longitudinal motion.

Figure 8 variation of forces (moments) on two kinds of moored floating bodies

The force and moment variation of the mooring buoy directly affect the motion response of the buoy by degree. As the environmental force, gravity and buoyancy of wind and wave flow always exist, the floating body always has mechanical fluctuations along the X and Z axes, as shown in figure 8 (a) and (b). In the Y-axis direction, the resultant force is small at the beginning of time domain analysis of the tensioned moored floating body, and then the amplitude gradually increases and tends to be stable, which is consistent with the changing law of the floating body's

oscillation motion in figure 5 (a). Although the net force of the catenary mooring floating body is close to 0 in the Y-axis direction, the amplitude of mooring tension of,, and cables is still large, with the maximum value of $6.5 \times 10^4 \text{N}$, which still affects the bearing capacity and service life of the floating body. In figure 8 (c) (d), the law of moment variation is similar to that in figure 8 (a) (b). Due to two types of mooring on the Y axis motion response and mechanical change is mainly affected by the mooring force, so this article in the argument mooring floating body at the same time, the change regularity and mechanical movement response relationship based on 6 dof decoupling equation of motion to improve the traditional floating mooring arrangement, optimization of mooring floating of strength properties and the movement stability.

3. The mooring scheme is optimized based on the six-degree-of-freedom decoupling equation

Mooring floating body based on the above analysis of six degrees of freedom movement response and mechanical change law of traditional mooring method optimization scheme is put forward, taking the environmental force of wind wave flow at 0° incident direction as an example, the incident direction and flow force bearing direction because of the X axis is given priority to, Y axis force is lesser, stormy waves flow negligible, therefore to consider in the X direction to strengthen mooring line bearing capacity and stability of floating body movement, in the Y simplify the structure of mooring cable. Based on the traditional tensioning and catenary mooring structures, the optimal design is shown in figure 9.

(a) Two way mooring optimization scheme

(b) Four way mooring optimization scheme

Figure 9 Mooring optimization scheme model

As shown in figure 9 (a) (b), based on the traditional six direction mooring line arrangement, considering the characteristics of mooring motion and mechanical performance optimization in x-axis and y-axis two degree of freedom direction, the No.1- No. 6 cable is rearranged, and the two-way and four-way mooring scheme optimization models are established respectively. In order to ensure the reliability of the optimization scheme model, the environmental parameters and mooring floating body parameters remain unchanged. The time domain simulation analysis of the optimization model is carried out respectively, and the motion response and mechanical change law are obtained, as shown in figure 10 and figure 11.

Figure 10 comparison of motion response of three mooring schemes

In order to verify the superiority of the optimized mooring scheme, the influence

results of the main degrees of freedom of tension type and catenary type are compared and analyzed. The traditional catenary mooring has poor stability in the surge direction, as shown in figure 10 (a). Comparing the traditional six direction mooring scheme with the optimized two-way and four term mooring schemes, the two-way mooring scheme has shorter stable oscillation time and better stability effect, and the three schemes have similar operation response effect in other degrees of freedom direction, so the specific analysis is no longer needed. The traditional tension mooring system has poor stability control in the direction of two degrees of freedom of sway and roll, as shown in Figure 10 (b), (c) and (d). Compared with the optimized two-way and four term mooring schemes, the four-way arrangement system has better stability. The two-way arrangement system has smaller amplitude of sway in the early stage of time domain simulation, and gradually increases amplitude in the later stage, resulting in poor stability effect. The results show that the mooring effect is the best when the tight constraint is large and the mooring line layout direction is balanced and vertical with the wind, wave and current load direction.

Figure 11 Comparison of tension extremum of three mooring schemes

In terms of the change of mooring tension, as shown in figure 11 (a), the maximum value of the optimized catenary two-direction and four-direction arrangement of mooring tension is better than that of the six-way arrangement, in which the tension distribution of the two arrangements is more balanced and the control effect is better. In figure 11 (b), the change effect of tension values of each

cable of tensioned mooring before and after optimization is not obvious. Considering that tensioned mooring cables have strong self-restraint and are greatly affected by the oscillation of the floating body, the mooring tension changes less under different arrangement schemes.

4 summarizes

(1) Based on the decoupling analysis method, established the mooring state down six degrees of freedom movement and mechanics relationship equation, combined with the simulation analysis result, has been clear about the mooring floating body in six degrees of freedom motion responses and mooring tension force and buoyancy correspondence, wind flow, for the study of the motion law of the sea mooring floating equipment optimization and stability provides a theoretical basis.

(2) Combined with the motion equation and the multiple degree of freedom simulation results, in the process of time domain analysis, the magnitude and direction of the wind and wave flow environmental force F_E , buoyancy F_B and gravity F_G subjected to the mooring body remain basically unchanged, so the motion state and stability of the floating body are mainly changed by controlling the mooring force F_M .

(3) The influence of different mooring methods on the motion of the floating body with different degrees of freedom is analyzed. The results show that the tensioned mooring floating body has large motion response in the five degrees of freedom directions of surge, sway, roll, pitch and yaw; the catenary mooring floating body has large motion response amplitude in the three degrees of freedom directions of surge, heave and pitch, and large motion response amplitude in the three degrees of freedom directions of sway, roll and yaw. The amplitude is small.

(4) Combined with the motion response and mechanical law of the two traditional tensioning and catenary mooring schemes in the direction of six degrees of freedom, the two-directional and four-directional mooring optimization schemes were proposed. Through simulation comparison, the advantages of the two-directional and four-directional mooring schemes in the motion response and mechanical properties of the multiple-degree-of-freedom floating body were verified.

Reference:

- [1] Wang Cui, Cai Ling, Wu Yaojian, Ouyang Yurong. Numerical simulation of the impact of an integrated renovation project on the Maowei Sea hydrodynamic environment.[J]. Scientific reports, 2021, 11(1):
- [2] Xu Yunxin, Shi Weichao, Arredondo Galeana Abel, Mei Lei, Demirel Yigit Kemal. Understanding of remora's "hitchhiking" behaviour from a hydrodynamic point of view[J]. Scientific Reports, 2021, 11(1):
- [3] A.P. Shashikala, R. Optimisation of heaving buoy wave energy converter using a combined numerical model[J], Applied Ocean Research. 102 (2020), pp. 135-147
- [4] T. Fan, D. Qiao, J. Yan, et al. An improved quasi-static model for mooring-induced damping estimation using in the truncation design of mooring system[J], Journal of Hydrodynamics, 136 (2017), pp. 322-329
- [5] A.P. Shashikala, R. Sundaravadivelu, C. Ganapathy Dynamics of a moored barge under regular and random waves[J], Scientific Reports, 24 (5) (2017), pp. 401-430
- [6] C. Barrera, R. Guanche, I.J. Losada Experimental modelling of mooring systems for floating marine energy concepts[J], Mar. Struct., 63 (2019), pp. 153-180
- [7] Mavrakos, Chatjigeorgiou. Dynamic behaviour of deep water mooring lines with submerged buoys[J], Comput Struct. 64 (1) (1997), pp. 819-835
- [8] J. Azcona, D. Palacio, X. Munduate, L. González, T.A. Nygaard Impact of mooring lines dynamics on the fatigue and ultimate loads of three offshore floating wind turbines computed with IEC 61400-3 guideline[J], Wind Energy, 20 (2017), pp. 797-813
- [9] S. Liu, Y.L. Zhang. Numerical simulation of multipledirectional irregular wave group propagation[J]. Journal of Tsinghua University, 55 (12) (2015), pp. 1289-1295
- [10] L. Wang, Y. Tang, X. Zhang, J. Zhang Studies on parametric roll motion of ship under wave group by numerical simulation[J], Scientific Reports, 163 (2018), pp. 391-399
- [11] T.J. Xu, Y.P. Zhao, G.H. Dong, F.K. Gui, Analysis of hydrodynamic behavior of a submersible net cage and mooring system in waves and current[J], Applied Ocean Research, 42 (2013), pp. 155-167

[12] B. Teng, P.W. Cong. A novel decomposition of the quadratic transfer function (QTF) for the time-domain simulation of non-linear wave forces on floating bodies [J], Applied Ocean Research, 65 (2017), pp. 112-128

[13] Lu Jiangnan, Niedzwecki J.M.. Analysis of Random Wave Interaction with Cylinders using Extremal Statistical Methods[J]. Scientific Reports,2020,105.

[14]Zhang Xiaoguang, etal. Research on inflation and floating-up process of unmanned underwater vehicle based on collaborative simulation technology[J]. Applied Ocean Research,2020,105.

[15]Hu Xin,Wei Xinjiang, etal. Composite anti-disturbance dynamic positioning of vessels with modelling uncertainties and disturbances[J]. Applied Ocean Research,2020,105.

[16]Viuff Thomas,etal. Model uncertainty assessment for wave- and current-induced global response of a curved floating pontoon bridge[J]. Scientific Reports,2020,105.

Acknowledgments

This work is financially supported by the Qingdao West Coast new area science and technology project in 2019 (2019-8) "Research on Key Technologies of marine fishery electricity integrated development system" and National Natural Science Foundation of Shandong China Joint Fund (No.sv2017-kf-02).