Research Article

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Displacement Reliability Analysis of Submerged Multi-body Structure's Floating Body for Connection Gaps

<https://doi.org/10.1515/phys-2019-0029>

Received Dec 16, 2018; accepted May 01, 2019

Abstract: Aiming at the problem of systems' dynamic characteristics' randomness caused by connection gaps of submerged multi-body structures, a stochastic and uncertainty dynamical model were formulated for connection gaps and dynamic elongation of mooring cables. This model considered sag effect caused by light, soft and low damping characteristics of mooring cables and their dynamic elongation under the impact of flow field and connection gaps. The equivalent elastic modulus method was used to modify the sag effect. The Newmark- β method was used to solve the problem. Calculation results showed that the average value and peak value of floating body displacement caused by uncertainty of gap contact states are larger than those of ideal articulated states. The reliability of floating body's displacement with gap contact will be reduced to different extents and the reliability of displacement in velocity direction changes greatly, especially perpendicular to flow field. When studying multi-body structures, randomness of contact state should be considered to reduce the dispersion of clearance and improve dynamic performance.

Keywords: Submerged multi-body structures; connection gaps; contact state; displacement reliability

PACS: 07.10.2h, 33.20.Tp

1 Introduction

A submerged multi-body structure is the main support structure of a floating platform, such as the floating foundation of a wind turbine, suspended tunnel submerged mooring monitoring platform. A submerged multi-body structure is composed of both flexible structures and rigid structures. In previous research external loads and boundary conditions have been considered as accurately determined or accurately measured and the connections between the mooring cables and the structures have been coupled as the boundary conditions, without considering the contact states between them [1–7]. However, in actual situations the external loads, boundary conditions and contact states of multi-body structures are stochastic and uncertain because of the movement of and joint clearances between mooring cables and the structure. These lead to uncertainty of the dynamic characteristics [8–10], so this paper is aimed at a basic dynamic model of submerged multi-body structures, the dynamic characteristics of mooring cables and the joint clearances between the mooring cables and the structure [11–15].

Connections between mooring cables and submerged multi-body structures are usually hinged [16, 17]. Connections need certain clearances for inaccurate assembly, so friction and wear in motion will occur. Consequently the joint clearances with change of time. All of these would lead to deviation and uncertainty between the theoretical motion and the actual motion of structures [18, 19]. Structures have important positioning and supporting functions in a system, the deviation of its position will lead to unreliable system conditions. During the course of movement, the deviation will cause collisions with connection contacts, which will affect stability and precision of motion and even the whole life of the system. In turn, this will cause uncertainty of the system's motion state and deviation of its function [20]. Therefore, it is necessary to study the dynamic characteristics of submerged multi-body structures caused by joint clearance. This would bring theoretical analysis results closer to engineering

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practice and provide a theoretical basis for the design of such structures.

With continuous improvement of computing technology and development of hydrodynamic theory predictions of the dynamic response and stress of a submerged multi-body structure under different environmental conditions have been obtained by theoretical calculations [21–23]. Researchers have carried out relevant studies on different types of concrete structures. Based on the multi-component catenaries equation, Ravi *et al.* analyzed the design and combinatorial optimization of a deep water catenaries mooring system, and restoring stiffness of the catenaries anchor cable. It is found that the recovery coefficient of the anchor chain shows strong nonlinear characteristics, so the influence of its geometric nonlinearity cannot be ignored in the course of research [24]. Tcheou *et al.* studied different types of cables based on the catenaries equation, and derived analytical expressions for cable tension distribution and geometry [25]. Zarruk *et al.* used a set of parameters to approximate external excitation of anchor cables for consideration of external forces. The above catenaries method ignored some external forces such as fluid force acting on mooring cables, which is an approximate solution to a practical problem [26]. Yougang *et al.* studied the influence of mooring cables' shape and tension on deep-sea platforms by numerical simulation and a finite element method. Numerical simulation results were compared with experimental results with good agreement [27]. Ruoyu *et al.* analyzed deep-sea mooring of semi-submersible platforms by an indirect time domain coupling method, in which calculation of the wave force is accurate to second order, and the control equation of mooring cables is solved by a lumped mass method [28]. Smith *et al.* further developed second-order perturbation theory for dynamic analysis of mooring cables. This method takes into account the influence of nonlinear, dynamic coupling of the mooring system and the slow-drift response of a floating body [29]. He Kongde *et al.* studied the forces on mooring cables and structures based on the theory of impact dynamics and analyzed the motion state of mooring cables before and after impact [30]. There are few references about the reliability of floating body displacement. The results of traditional, deterministic system dynamics models are also deterministic, so it is impossible to verify the reliability of the dynamic behavior of a system [31]. All of the above studies take the connection of mooring cables and structures as boundary conditions and do not consider the actual contact state between them. This paper takes a certain type of mooring multi-body structure as a research object and establishes a stochastic, dynamic, analysis model of the nonlinear interaction between the flow

field structure and mooring cables by applying boundary conditions of the hinge at mooring points and considering their coupling contact state. On the basis of this, the reliability of floating body displacement is further studied.

2 Establishment of a multi-body structure model

Figure 1 shows a multi-body structure model with joint clearances, which works in a certain depth of water. 1 is a

(A) General layout of model

(B) Enlargement drawing of structure-connection plate

(C) Enlargement drawing of mooring cable-axis pin

Figure 1: Diagrammatic figure of mooring multi-body structure with joint clearance

mooring cable with the upper end connected to a connecting plate through a shaft sleeve at 5 and the lower end anchored in water, 2 is the structure, 3 is a connecting plate, 4 is an axis pin and 5 is a shaft sleeve.

3 Building a dynamic model

The movement of the structure is mainly in the plane of the flow field direction. Its motion state is related to the depth of its placement in the flow field, the velocity of the flow field and the shape of the transverse section of the structure. According to the research results in reference [33], a mooring structure, which is placed in a certain depth of water, will be subjected to a flow force along the axial direction of the floating body and lateral and axial flow resistance. Figure 2 is a simplified schematic diagram.

Figure 2: Simplified schematic plot of mooring multi-body structure

The structure is subjected to drag force in the direction of the current based on the resistance of the fluid, the buoyancy of the flow field, its own gravity and the restraining force of the mooring cables. O-point is the initial position of the geometric center of the structure according to the coordinate system shown in Figure 2. According to fluid dynamics theory, a moving object in a flow field will also bring about the same amount of fluid as the volume of the floating body when it moves. The flow strength of the mooring cables can be neglected due to the ratio of the structure's sectional dimension to the mooring cable's sectional dimension. So the dynamic equation of a submerged mooring multi-body structure is established according to New-

ton's Law of mechanics.

$$m \frac{d^2 Y}{dt^2} + C \frac{dY}{dt} + KY = F_Y \quad (1)$$

$$m \frac{d^2 Z}{dt^2} + C \frac{dZ}{dt} + KZ = F_Z \quad (2)$$

Where m is the mass of the structure and the mass of liquid discharged by the floating body, K is the stiffness coefficient of the mooring cables and C is the hydrodynamic damping coefficient. F_Y and F_Z are fluid forces of structure, according to the coordinate system shown in Figure 2. F_Y is the sum of forces on the structural body in vertical liquid plane direction which include the fluid lift F_L and the Y-direction inertia force F_{IY} . F_Z is the sum of forces of the structure in the flow field direction which includes the fluid drag force F_d and the direction inertia force F_{IZ} .

3.1 Solution of Flow Field Force

According to fluid dynamics theory, the force of a flow field can be calculated according to the Morison equation. Since the ratio of the diameter of the structure to the depth of the flow field is very small, the flow field acts on the structure with uniform velocity. The fluid lift force F_L , inertia force in Y-direction F_{IY} , fluid drag force F_d and inertia force in Z-direction F_{IZ} is as follows:

$$F_L = C_L \frac{1}{2} \rho v^2 D L \quad (3)$$

$$F_{IY} = C_M \rho \pi \frac{D^2}{4} \frac{d^2 Y}{dt^2} L \quad (4)$$

$$F_d = C_D \rho \frac{D}{2} \left| v - \frac{dZ}{dt} \right| \left(v - \frac{dZ}{dt} \right) L \quad (5)$$

$$F_{IZ} = C_M \rho \pi \frac{D^2}{4} \frac{d^2 Z}{dt^2} L \quad (6)$$

Where C_L is the fluid lift coefficient, ρ is the fluid density, v is the flow field velocity, D is the structure's diameter, L is the length of the floating body, C_M is the inertia coefficient and C_D is the flow field resistance coefficient.

3.2 Solution of mooring cables' elastic tension and damping force under action of flow field

3.2.1 Solution of mooring cables' stiffness coefficient

In a submerged multi-body structure, mooring cables are the main constraint components. Mooring cables are characterised as lightweight, simple form of force and able

to give full play to mechanical properties of the material. Mooring cables are subjected to random wave loads, because of their lightweight, soft and low damping characteristics, so the whole multi-body structure system is prone to large vibration under the action of external random loads. As shown in Figure 3, due to the existence of joint clearances, the contact state of the connection will also be changed which will also cause large vibrations. These kind of large vibrations will cause the lengths of the mooring cables to change and so the impact forces at the connections will also change. This will affect the security, durability and positioning of the whole system [34]. Therefore, in order to solve the elastic tension of the mooring cables, elastic elongation of the mooring cables under the action of the flow field should be considered along with elastic elongation of the mooring cables caused by impact forces under uncertain connections. When solving the problem, the influence of sag should be considered for flexible members with certain configurations. According to reference [35], the equivalent elastic modulus method is used to modify sag effect of flexible members. The formulas are as follows:

$$E_{eq} = \frac{E}{1 + \frac{(ql_x)^2 EA_c}{12T^3}} \quad (7)$$

Where E_{eq} is the equivalent elastic modulus of the mooring cables, E is the elasticity modulus of the material, q is the line density of the material, l_x is the projected length of the flexible members in the velocity direction, A_c is the cross-section area of the mooring cables and T is the tension of the initial equilibrium position. Figure 4 shows a

Figure 3: Enlargement drawing for joint clearance at the connection point A, B

Figure 4: Force diagram of submerged multi-body structure on static balance position

force analysis diagram of the submerged multi-body structure at a certain depth.

Where W is gravity on the structure and attachments and F is the buoyancy of the structure and appendages. The multi-body structure is in temporary equilibrium under the force of gravity, buoyancy and the restraining force of the mooring cables. The tension of cable is:

$$T_1 = T_2 = \frac{F - W}{2 \sin \theta} \quad (8)$$

According to material mechanics theory, the stiffness coefficient of the mooring cables is obtained as follows: $K = \frac{E_{eq} A_c}{l}$.

3.2.2 Solution of damping coefficient

According to fluid dynamics theory, the damping coefficient C can be obtained by the following formula:

$$C \approx \frac{4\omega}{3\pi} \rho C_D A_L U \quad (9)$$

Where ω is the natural angular frequency of the structure, A_L is the structure's cross-sectional area in the direction of velocity and U is the amplitude of the steady response of the cables.

For restraining force of mooring cables and flow field force, a dynamic model of the submerged multi-body structure is established according to formulae (1) and (2):

$$\left(m + C_M \rho \pi \frac{D^2}{4} L \right) \frac{d^2 Y}{dt^2} + CL \frac{dY}{dt} + K \sin \theta_1 \cos \theta_1 Y \quad (10) \\ = C_L \frac{1}{2} \rho v^2 DL + (F - W)$$

$$\left(m + C_M \rho \pi \frac{D^2}{4} L\right) \frac{d^2 Z}{dt^2} + CL \frac{dZ}{dt} + K \frac{\cos^3 \theta_1}{\sin \theta_1} Z \quad (11)$$

$$= C_D \rho \frac{D}{2} \left| v - \frac{dZ}{dt} \right| \left(v - \frac{dZ}{dt} \right) L$$

4 Establishment of stochastic dynamic model for joint clearance

4.1 Solution of elastic elongation of mooring cables for joint clearance

A multi-body structure in a certain depth of water has initial equilibrium position, which will deviate under external random wave and current loads. Assuming that joint clearance is not taken into account, the elastic deformation of the mooring cables under the external force is u_i as shown in Figure 2. According to the overall deformation coordination conditions of the submerged multi-body structure, u_i can be obtained by the following formulae:

$$u_1(t) = l'_1 - l_1 = Y(t) \cos \theta_1 + Z(t) \sin \theta_1 \quad (12)$$

$$u_2(t) = l'_2 - l_2 = Y(t) \cos \theta_2 - Z(t) \sin \theta_2 \quad (13)$$

Considering joint clearance between the mooring cables and the connecting positions on the structure, as shown in Figure 3, the topology of whole system will be changed under the action of a random flow field. Correspondingly, the length of the mooring cables will be changed randomly. The range of length of the mooring cables is as follow:

$$0 \leq u_1(t)' \leq Y(t) \cos \theta_1 + Z(t) \sin \theta_1 + 2r_c \quad (14)$$

$$0_c \leq u_2(t)' \leq Y(t) \cos \theta_2 + Z(t) \sin \theta_2 + 2r_c \quad (15)$$

Where $r_c = r_j - r_s$, r_j is the inner diameter of the shaft sleeve and r_s is the outer diameter of the axis pin.

4.2 Establishment of dynamic model for joint clearance

As shown in Figure 3, the topology of whole system will be changed under action of a random fluid field because the clearance between the mooring cables and the connecting position on the structure. A lot of research has been done on how to establish an accurate and solvable dynamic model of a multi-body system for clearance [36].

There are three kinds of methods be adopted currently: ① Continuous contact model; ② Three-state model; ③ Two-state model. The continuous contact model assumes that the axis pin and the inner wall of the shaft sleeve are always in contact, the contact surface is without elastic deformation and collision and separation of contact are not considered. This method will be more convenient to solve but fails to show dynamic characteristics of clearance collision and separation. The three-state model mainly considers three states of free, collision and separation of the axis pin and the inner wall of the shaft sleeve in one cycle. This analysis method can reflect dynamic characteristics of contact and collision well, but the difficulty is how to accurately determine the collision time of three states in one cycle, so this method is very complex and is not widely used. The two-state model is a common method when analyzing multi-body systems for the effect of clearance. This model considers that there are only two states of contact and freedom between the axis pin and the inner wall of the shaft sleeve, and the hertz contact force model and continuous contact force model are used to express the collision relationship.

Based on constraint relations of contact force, the coupling between axis pin and the inner wall of the shaft sleeve can only be constrained by contact collision normal force and tangential friction. There is no other constraint relation. As shown in Figure 3, the clearance size is r_c , r is the center distance, assuming that a certain depth of penetration occurs during the collision, the penetration depth is:

$$\delta = r - r_c \quad (16)$$

The contact force between axis pin and the inner wall of the shaft sleeve can be calculated by impact function, the impact function model is equivalent to a nonlinear spring model based on penetration depth. The expression is:

$$F_N = \begin{cases} KJ(\delta)^n & \delta < 0 \\ 0 & \delta \geq 0 \end{cases} \quad (17)$$

Where K_J is the contact stiffness coefficient, δ is the penetration depth and n is the nonlinear spring force index with a value of 1.5 for metallic materials. When $\delta > 0$, two objects do not come into contact and the contact force is 0. When $\delta < 0$, two objects come into contact and the contact force is related to the contact stiffness coefficient and a nonlinear exponent.

According to hertz contact theory, the contact stiffness coefficient of the object is related to material properties of the object and the geometrical shape of the contact surface.

Contact stiffness of contact surface can be calculated according to the formula of contact stiffness provided in reference [37], and the formula is as below:

$$K_J = \frac{4}{3\pi(h_1 + h_2)} \left(\frac{R_1 R_2}{R_1 + R_2} \right)^{1/2} \quad (18)$$

Where R_1 and R_2 are the curvature radii of the axis pin and the inner wall of the shaft sleeve respectively, its values are r_j and r_s , h_1, h_2 are material parameters, which are defined as: $h_i = \frac{1-u_i^2}{\pi E_i}$; $i = 1, 2$, u_i is the material poisson ratio and E_i is the material modulus of elasticity.

Since the axis pin and the inner wall of the shaft sleeve are considered to be constrained by collision normal force and tangential friction. Under the action of tangential friction, relative slippage or stickiness will occur, which will affect the dynamic characteristics of system. Therefore, the friction must be considered in the calculation process and the most commonly used friction model is the coulomb friction model. According to the definition in reference [38], the coulomb friction model considered gap-contact is corrected and the relation expression of friction and velocity is as follows:

$$F_t = -uF_N \frac{v}{|vt|} \quad (19)$$

Where u is the coulomb friction coefficient, v_t is the tangential relative motion velocity and F_N is the normal contact force of axis pin and shaft sleeve.

4.3 Stochastic dynamic model for dynamic elongation and clearance-contact of mooring cables

According to equations (10) and (11), considering contact force, friction and dynamic elongation of mooring cables, a stochastic generalized multi-body dynamics model can be established. The generalized coordinates of the system are defined as $q = [q_1^T q_2^T]^T$. $q = [q_i^T \theta_i^T]^T$ ($i = 1, 2$) is the general coordinate of the floating body in the coordinate system, $r_i = [r_{iy}^T r_{iz}^T]^T$ is the position coordinate vector and θ_i is the angle of mooring cables and axis Z. According to above analysis, the dynamic equation for wear of joint clearance can be obtained and the Lagrange multiplier method is used to establish a generalized dynamic equation as follows:

$$\begin{bmatrix} M & \varphi_q^T \\ \varphi_q & 0 \end{bmatrix} \begin{bmatrix} \ddot{q} \\ \lambda \end{bmatrix} = \begin{bmatrix} F \\ \gamma \end{bmatrix} \quad (20)$$

Where M is generalized mass matrix of system, φ_q is Jacobi matrix of constrained equation, λ is Lagrangian multiplier, F is generalized force matrix of system, which contains three terms, which are generalized force matrix of external force in generalized coordinate system, matrix force related to quadratic term of velocity, normal force caused by collision and matrix of friction force in generalized coordinate system.

$$\gamma = -\left(\varphi_q \dot{q} \right)_q \dot{q} - \varphi_u - 2\varphi_{qt} \dot{q} \quad (21)$$

The equation (21) synthesizes the motion state of submerged multi-body structure under the action of flow field and combination of normal force and friction, which can be used to analyze stochastic dynamic response of submerged multi-body structure in the condition of stochastic load and uncertain contact wear.

5 Stochastic Analysis of Dynamic Response

Considering dynamic elongation of the mooring cables and joint wear, the topological structure of the whole system will change under action of a stochastic fluid field. The length of the mooring cables is an uncertain parameter; probabilistic, fuzzy and interval methods are generally used to deal with uncertain parameters in practical problems [38]. The probabilistic and fuzzy methods need enough data to determine the probability density distribution function and membership function of parameters whereas the interval method only needs to know range of the parameters. According to formulae (14) and (15) the stochastic dynamic response of submerged multi-body stochastic structures with connection gaps is analyzed by the interval method. Considering the length of the mooring cables as an intervals variable, according to the above analysis, the stiffness coefficient K and resistance coefficient c have interval properties. Considering the flow field force is also an uncertain parameter, the generalized equation (20) of multi-body structure dynamics for gap contact will be a time-varying second order differential equation group. So the Newmark- β method is adopted to solve the problem and the dynamic equation is transformed into a step-integral scheme, interval algorithm is used to solve it.

$$K_{t+\Delta t} \delta_{t+\Delta t} = p_{t+\Delta t} \quad (22)$$

$$K_{t+\Delta t} = K + C\alpha(\beta\Delta t) + M(\beta\Delta t^2) \quad (23)$$

$$p_{t+\Delta t} = p + M \left[\frac{\delta_t}{\beta \Delta t^2} + \frac{\dot{\delta}_t}{\beta \Delta t} + \left(\frac{1}{2\beta} - 1 \right) \ddot{\delta}_t \right] + C \left[\frac{\alpha \delta_t}{\beta \Delta t} + \left(\frac{\alpha}{\beta} - 1 \right) \delta_t + \left(\frac{\alpha}{2\beta} - 1 \right) \Delta t \ddot{\delta}_t \right] \quad (24)$$

Where α and β are integral parameters, Δt is the integral step, M , K and C are mean values of mass matrix, stiffness matrix and resistance matrix, subscript t is the corresponding state parameter for some time. According to formulae (14) and (15), the upper and lower limits of elastic displacement of the mooring cables are $u_i(t)_{t+\Delta t}'$ and $u_i(t)_{t-\Delta t}'$. The upper and lower limits of equivalent stiffness and equivalent load of time-varying characteristics can also be calculated.

6 Reliability Analysis of Floating Body Displacement

6.1 Functional Function of Floating Body Displacement

The calculated result of the floating body displacement of the above ideal hinge model must be a definite value. Considering the contact dynamic model of the gap, the calculated displacement of floating body must be stochastic and there will be a certain degree of deviation between them. Assuming that the allowable displacement error of the floating body is Δs , the reliability of its displacement can be defined as a probability, the actual displacement error deviates from the allowable displacement error. Therefore, the function of displacement reliability can be established as follows:

$$g(i) = \Delta S - (S_c - S_l) \quad (25)$$

Where S_c is the actual displacement value of the floating body at some time considering gap contact, S_l is the ideal displacement value of the floating body at some time. The displacement value can also be decomposed according to the coordinate direction of kinetic equation, so the displacement value and the displacement reliability function of the floating body in the direction of flow and depth are obtained.

6.2 Calculation of Displacement Reliability of Floating Body

According to the generalized equation of multi-body structure dynamics considering gap contact, the interval variable range of mooring cable length and the step length Δt

and integral interval t of the Newmark- β method, the distribution parameters of floating body displacement can be obtained:

$$u = \frac{\Delta t}{t} \sum_{i=1}^{\frac{t}{\Delta t}} g(i) \quad (26)$$

$$\sigma^2 = \frac{\Delta t}{t - \Delta t} \sum_{i=1}^{\frac{t}{\Delta t}} [g(i) - u] \quad (27)$$

Where i is calculation time, u is ideal displacement value of floating body at some time, and σ^2 is the variance of displacement. It is generally believed that the variation of mooring cable length and the gap error of the kinematic pair obey the normal distribution, and the superposition of the distribution is still under normal distribution, thus the error of the floating body displacement obeys the normal distribution [39], the reliability of the floating body displacement can be expressed as follows:

$$R = \varnothing(\beta) \quad (28)$$

$$\beta = \frac{u_0 - u}{\sqrt{\sigma_0^2 - \sigma^2}} \quad (29)$$

Where u_0 and σ_0 are the mean and variance of the allowable limit displacement of the floating body, u and σ are the mean and variance of the displacement of the floating body.

7 Numerical Examples

The submerged multi-body structure model for joint clearance is shown in Figure 1. At initial equilibrium position, the structural parameters, mooring cables parameters and hydrodynamic coefficients of flow field are shown in Table 1, and the lower end of mooring cables is anchored together with the bottom of the flow field.

Figure 5 and Figure 6 show the response history of Y-direction and Z-direction displacement of the floating body in gap contact model and hinged model with time. It can be seen from the figure that the displacement response of the floating body between the gap contact model and the hinge model is inconsistent with change of time, which indicates that the connection gap will have a certain effect on floating body displacement. This may lead to failure of the floating body function and dynamic performance, so the influence of gap must be considered in reliability analysis. Figure 7 and Figure 8 show the response history of the maximum, minimum and mean values of the Y-direction and Z-direction displacement of the floating body when

Table 1: Design parameters

Fluid density $\rho(\text{kg/m}^3)$	1×10^3
Coefficient of inertia force of flow field C_M	1
Depth of flow field $H(\text{m})$	63.2
Distance from the center of the structure to the surface $h(\text{m})$	10
Resistance coefficient of flow field C_D	0.4
Average velocity of flow field in the center of a structural body $V_m(\text{m/s})$	2.27
Lift coefficient of flow field C_L	0.07
Length of structural body $L(\text{m})$	50
Diameter of structural body $D(\text{m})$	0.2
Mass of structural $m(\text{kg})$	1463
Diameter of mooring cable $d(\text{m})$	0.006
Density of mooring cable $\rho(\text{kg/m}^3)$	6.46×10^3
Elastic modulus of mooring cable $E(\text{Pa})$	1×10^{11}
Number of mooring cables	6
Initial angle between mooring cable and Horizontal plane $\theta(^{\circ})$	21°

Figure 5: Time-distance Graph of Displacement Response on Y-Direction for Floating body **Figure 6:** Time-distance Graph of Displacement Response on Z-Direction for Floating body **Figure 7:** Average Value of Displacement Response on Y Direction for Floating Body **Figure 8:** Average Value of Displacement Response on Y Direction for Floating Body **Figure 9:** Mean Square Error of Displacement Response on Y Direction for Floating Body

Table 2: Displacement Reliability for Floating Body

variation coefficient of contact state of gap		Y direction 0.01	Z direction 0.01
Displacement error of floating body	Mean value of displacement of floating body (mm)	353.924	135.4186
	Difference in the floating position (mm)	27.4154	4.7572
	Reliability of displacement of floating body	0.8375	0.9342

Figure 10: Mean Square Error of Displacement Response on Y Direction for Floating Body

considering gap contact and ideal hinge respectively. Figure 9 and Figure 10 show the response history of the mean square deviation of Y-direction and Z-direction displacement of floating bodies with time. Table 2 shows the reliability of Y-direction and Z-direction displacement of the floating body when coefficient of variation of gap contact is 0.01[40]. The results show that displacement reliability of the gap contact model is obviously lower than that of ideal hinge model, especially that of the Y-direction displacement.

8 Conclusion

Taking a simplified general model of submerged multi-body structure as a research object, the clearance contact state and hinge state between mooring cables and structure has been considered. Based on the Morrison formula of fluid dynamics theory, force of flow field in different directions is calculated according to the shape of cross section of the structure, studied its stiffness for considering the flexible characteristics of mooring cables. According to uncertainty of multi-body dynamics for clearance contact, the two-state contact model was adopted to establish a dynamics model for dynamic elongation of mooring cables and clearance. Dynamic characteristics and displacement

reliability of the floating body were analyzed with an interval method and the following conclusions were obtained: ① Mean and peak value of the floating body displacement are greater than the ideal articulation state. ② Reliability of displacement of the floating body in the gap contact state can be reduced to varying degrees, especially the reliability of displacement perpendicular to the direction of the flow field. ③ The contact state model for joint clearance is more consistent with engineering practice. Therefore, when studying submerged multi-body structures, the contact state of joints should be taken into account and stochastic dynamic characteristics of the joints should be analyzed.

Acknowledgement: This study is support by National Natural Science Foundation of China (51775307; 51875314) and Design and maintenance of hydro-mechanical equipment opening fund of key laboratory of Hubei Province (China Three Gorges University) (2017KJX03).

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