Study on the Dynamic Behaviours of an Articulated Offshore Wind Turbine under the Severe Sea State

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ABSTRACT

In this paper, an articulated offshore wind turbine (AOWT), which consists of ballast tank, buoyancy tank and middle column, is proposed to solve the challenges that both fixed and floating offshore wind turbine couldn't meet in the the medium-water-depth areas. Through establishing high-dimensional three-objective optimization mathematical model, the main foundation dimensions are determined by non-dominated sorting genetic algorithm Ⅲ (NSGA-Ⅲ) and corresponding optimization algorithm code is programmed in the MATLAB development environment. In order to to verify the robustness of the AOWT, different severe sea states, including extreme wind speed and extreme stochastic wave scenarios are chosen. For survival sea state, as the turbine is in the parked condition, the aerodynamic load on rotating blades is ignored and the wind pressure loads are calculated based on the empirical formula. The first and second order wave loads are all considered, corresponding hydrodynamic coefficients are simulated by the 3-D potential flow theory. The simulations are conducted in the time domain and dynamic responses are numerically simulated by our in-house aero-hydro coupled code. In previous works, we have investigated AOWT dynamic behaviours under the operational scenarios. It is found that AOWT shows robust performance under the rated sea state. However, as a permanent moored offshore wind turbine, the AOWT will suffer different kinds of severe sea state during its lifetime. Towards this end, we performed a series of simulations to study the AOWT dynamic response under the severe sea status and the results of wave forces, tensions on the articulated joint and foundation motion in the pitch are summarized and analysed. Through the simulation results, we can have a clear understanding of the structure response. The safety and stability of AOWT under different severe sea states are thoroughly investigated, which reflect the validity of physical design to a certain extent. Furthermore, it also points out that the study of dynamic response under severe wave scenarios is necessary for structural design.

Keywords: articulated offshore wind turbine; non-dominated sorting genetic algorithm; dynamic response; aerodynamic load.

1. INTRODUCTION

Nowadays, with the impact of global warming, the trend of replacing traditional energy to renewable energy has been increasingly intensified. As one of the important energy resources, wind power has naturally become a hotspot of scientific research. Recently, environmental governance and carbon emission reduction targets are institutionalized into the government strategy [1], which is a great opportunity for the wind power industry. Among them, compared with the onshore wind turbine, offshore wind turbine [2] research has more potential and challenge. Nevertheless, the offshore scenario in China is totally different from the Europe. The average water depth of the eastern and southeastern coasts is approximately 50-100 meters[3], which is a great challenge to layout either floating or fixed offshore wind turbine in these areas in considering of economic cost and safety.

Based on the research of articulated tower platform [4] and offshore wind turbine, an articulated offshore wind turbine (AOWT), is proposed to solve the technical gap in this water depth range. Nowdays, the optimization design of foundation mostly adopts the single-objective optimization method [5], which pays too much emphasis on a certain target value while neglecting the influence of other factors. As a result, the optimization results are not systematic and scientific, and often deviate from the actual engineering. This paper uses non-dominated sorting genetic algorithm Ⅲ (NSGA - Ⅲ), which is a kind of multi-objective genetic algorithm based on the Pareto optimal solution. The NSGA was originally proposed by N. Srinivas et al. [6] in 1995, which is based on genetic algorithm and introduce the concept of dominant and non-dominant relation to sort multiple targets. In 2002, based on NSGA algorithm, an improved (NSGA Ⅱ) algorithm is proposed by Deb et al [7]. It uses nondominated sorting to ensure convergence quickly, and in order to make the solution more even in object space, the crowded degree concept is introduced to keep the population diversity. For higher dimensional target problems, K. Deb and H. Jain [8] proposed a third generation nondominated sorting genetic algorithm (NSGA - Ⅲ). Through importing the mechanism of extensive reference point, using a predefined target search method to keep individual species who are not dominated and more close to the reference point. For many practical problems, there are always equality or inequality constraints, and the dominant relation with constraints [9] is mainly used to deal with them.

For offshore wind turbine structures, multi-disciplines systems, including aerodynamics, hydrodynamics, controlling theory, etc. [10] are involved and the responses are highly coupled with each other components, which makes the whole system more sophisticated. In order to verify the safety and stability of the AOWT, it is necessary to establish the aero-hydro analysis system model and simulate the dynamic response under the corresponding sea states. Li et al. [11] simulated the OC3 Hywind Spar floating wind turbine by using the coupling method of multi-body dynamics and CFD, and compared the numerical results with the public data of NREL to verify the accuracy of the model. Kvittem et al. [12] used Dynamic Link Database (DLL) to write Aerodyn and DMS modules, which are suitable for solving aerodynamic loads of horizontal and vertical axis wind turbines. Combined with relevant hydrodynamic software of SESAM, they carried out time-domain coupling analysis on dynamic parameters such as foundation motion and mooring system tension of floating wind turbines. Bae et al. [13] took OC4 DeepCwind semi-submersible floating wind turbine as the research object, combined Charm3D and FAST software to establish an aero-hydro-servo-elastic- mooring coupling dynamic analysis model.

As an offshore towering structure, AOWT is permanent moored to the seabed, the dynamic response needs to take into account the effect of extreme wind and extreme stochastic wave. Pang [14] studied the loading of small-scale piles under extreme wave in a two-dimensional completely nonlinear numerical wave flume, and the high frequency resonance response of the structure is also investigated. Chen [15] established aero-hydro-servo coupling program for the offshore floating wind turbine, and carried out the analysis respectively under rated wind speed and extreme wind speed sea conditions. Yang [16] proposed a new type of semi-submersible wind turbine structure and conducted the time domain responses under the normal operating condition and extreme sea condition by using FAST software. The 6-DOF motion response results were obtained and verified with the experimental results.

In the following sections, structural design of AOWT foundation will be described firstly. Through establishing three-objective optimization mathematical model and writing the optimization algorithm program in the MATLAB development environment, a group of relatively optimal Pareto solutions were obtained. Based on the fuzzy optimization method [17], the evaluation index, weight factor and evaluation level of the fuzzy optimization scheme are determined [18], and the optimal scheme satisfying different evaluation indexes is obtained. Afterward, a brief introduction of numerical methodology is displayed, as well as the load cases. The simulations are conducted in the time domain and dynamic responses are numerically simulated by our in-house aero-hydro coupled code [19]. Then dynamic behaviours of the designed AOWT will be conducted under different severe sea states. Numerical results, including the aerodynamic performance, tensions on articulated joint and motion responses of the system are presented. In the last section of this paper, both conclusions and future works are summarized.

2. METHODOLOGY

2.1 Governing Equations in Time Domain

It is assumed that the articulated foundation and the upper wind turbine are all rigid body, the foundation column and the wind turbine tower are rigidly connected. The whole structure swings around the articulated joint in a single DOF motion [20]. The displacement, velocity and acceleration of AOWT are solved in time domain based on the Cummins equation of motion. The dynamic responses are subject to the wind, wave, current and hydrostatic restoring forces. Considering the pitch motion, the time-domain motion governing equation of AOWT can be expressed as:

$$\left[I+I_A(\omega)\right]\ddot{\theta}+\int_0^t h(t-\tau)\cdot\dot{\theta}(\tau)d\tau+D\cdot f(\dot{\theta})+K(\theta)\cdot\theta=q(t,\theta,\dot{\theta}) \tag{1}$$

Where $\ddot{\theta},\dot{\theta},\theta$ represent the pitch angle, angular velocity and angular acceleration, I is the moment of inertia of whole system, $I_A(\omega)$ is the additional moment of inertia, $h(t)$ denotes the retardation function and the Cummins model is used to solve, D is the nonliner damping matrix, f is the vector function of $\dot{\theta}$, K is the restoring matrix provided by buoyancy, q represent the exciting force vector, which includes the first- and second-order wave loads, wind pressure loads on the rotor and tower as well as the current drag force. Among them, wave loads are solved based on 3D potential flow theory, the hydrodynamic transfer function includes linear transfer function (LTF) $F_1(\omega)$ and the quadratic transfer function (QTF) $F_{2d}(\omega_1,\omega_2)$ and $F_{2s}(\omega_1,\omega_2)$ are calculated using hydrodynamic software WADAM[21]. Under the action of random waves, the first- and second-order wave loads in the time domain can be expressed as:

$$\begin{aligned}
F_{wave\_1}(t)&=\mathrm{Re}\left[\sum_{i=1}^{M}\eta_i F_1(\omega_i)\right]\\
F_{wave\_2s}(t)&=\mathrm{Re}\left[\sum_{i=1}^{M}\sum_{j=1}^{M}\eta_i\eta_j F_{2s}(\omega_i,\omega_j)\right]\\
F_{wave\_2d}(t)&=\mathrm{Re}\left[\sum_{i=1}^{M}\sum_{j=1}^{M}\eta_i\eta_j^{*} F_{2d}(\omega_i,\omega_j)\right]
\end{aligned} \tag{2}$$

Where η_i and η_j denote the wave elevation and its conjugation of i-th and j-th wave component in the complex domain. ω_i and ω_j are respectively the frequency of i-th and j-th wave components.

Futhermore, the drag force caused by current is considered and the two-dimensional cylinder model was applied. The calculation formulation[22] is shown as:

$$F_{cur}=\frac{1}{2}C_D\rho_W A V_{cur}{}^2 \tag{3}$$

Where, C_D is the drag force coefficient; ρ_W is the density of sea water; A is projected area of the component on the plane perpendicular to the current velocity.

When the wind speed exceeds the cut out wind speed, the turbine is in the parked state. The the upper wind turbine structure, including three blades and tower are subjected to the action of wind pressure load, and the aerodynamic force is no longer considered, which can be calculated on the following formulation[23]:

$$F_{wind} = 0.613\sum_{j=1}^{n}\left(C_h C_s A_i(\alpha) V_r^2\right) \tag{4}$$

Where, j is the number of component; n is the quantity of components; C_h is the height coefficient of component; C_s is the shape coefficient of component; $A_i(\alpha)$ is the projected area of component i on the α wind direction; V_r is the relative velocity between the wind and component. In the present study, an in-house aero-hydro coupled code was used to solve the motion equation of the AOWT system, and relevant program verification can refer to our previous research work [24].

1.2 Optimization Algorithm and Fuzzy Comprehensive Evaluation

Non-dominated sorting genetic algorithm III is a kind of multi-objective genetic algorithm based on the Pareto optimal solution. Through setting up objective functions, constraint conditions and decision variables, the optimization mathematical model is established, and a group of relative optimal solutions satisfying each optimization objective are obtained. On the basis of NSGA-II, the selection mechanism is improved, and the individuals of critical layer population are selected by widely distributed reference points [25]. The algorithm program is edited in the MATLAB development environment, and the specific process of optimization calculation is shown in the figure 1 below.

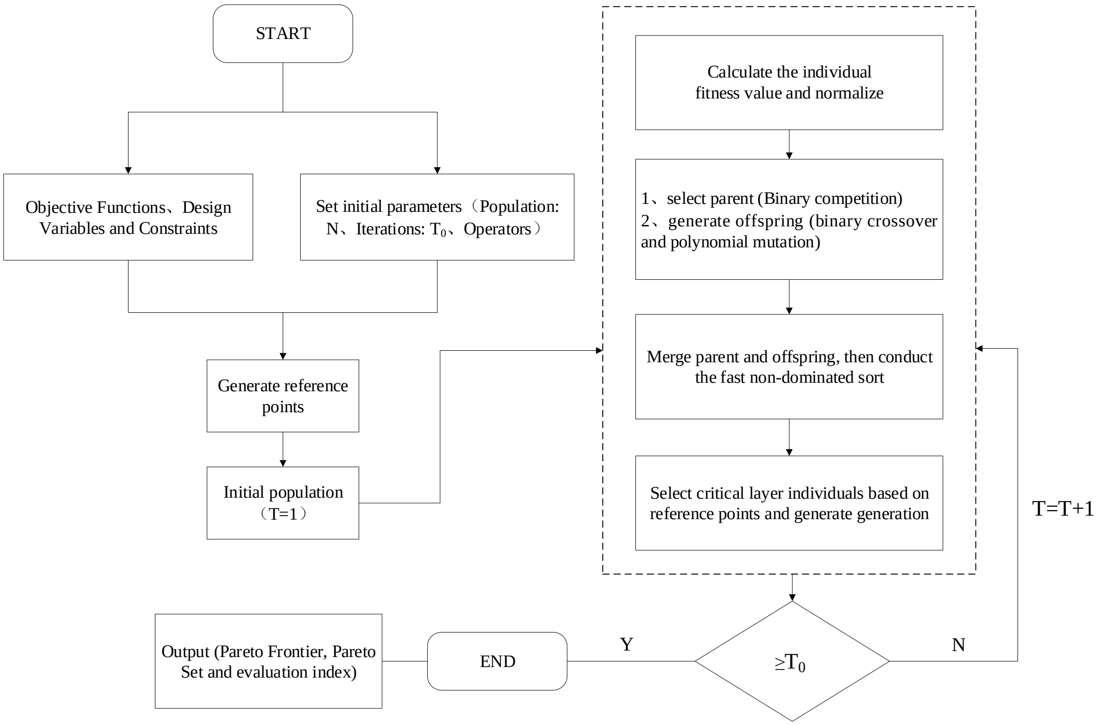


Figure 1. NSGA-III optimization process

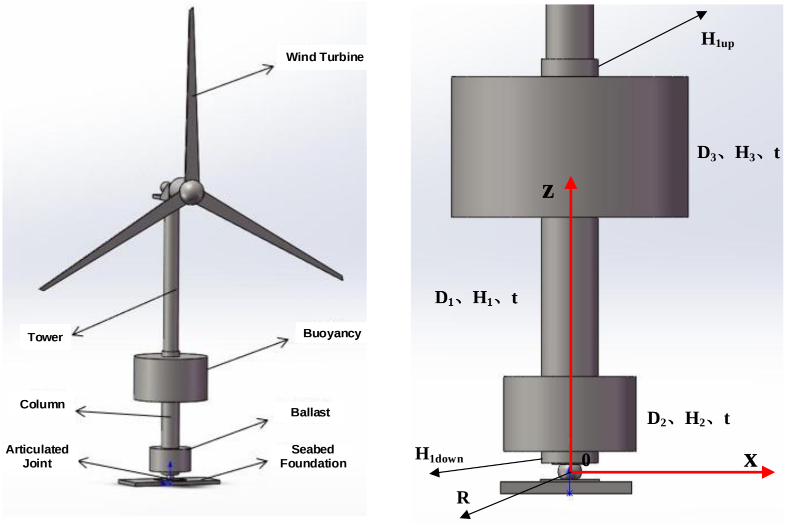
For most practical engineering problems, as there is no reference set, the related evaluation indexes of multi-objective optimization are not applicable. Furthermore, the optimization is affected by multiple factors, and the influence degree are not the same. In general, it is difficult to obtain a set of optimal solution directly from the obtained Pareto solution set. The fuzzy comprehensive evaluation is a kind of comprehensive evaluation method based on fuzzy mathematics, which transforms qualitative evaluation into quantitative evaluation according to the membership theory of fuzzy mathematics [26]. By determining the evaluation index, weight set and comprehensive evaluation score of the fuzzy optimal choice scheme, the final recommended scheme can be obtained from the Pareto solution set according to the final score. The mathematical model [27] is shown below:

$$R = \sum_i L_i \cdot T_i \tag{5}$$

Where R is the overall score, L is the weight set, T is normalized evaluation index.

3. MULTI-OBJECTIVE OPTIMIZATION FOR AOWT

Based on NREL-5MW wind turbine, an articulated offshore wind turbine is proposed for the water depth in 50 meters. AOWT is connected to the seabed foundation by the universal articulated joint and the environmental loads tilt the whole structure around the universal joint. Meanwhile, in order to avoid that the bottom of the ballast tank touch seabed and buoyancy tank emerge from water surface, there are remaining columns with the height of H_{1down}=2m and H_{1up}=5m respectively. Three-dimensional model of AOWT and its foundation structure are shown in figure 2. Hereby, (x, z) is a two-dimensional Cartesian coordinate system with its origin at the bottom of the articulated joint and z pointing upward (see Figure 2b). The x-axis coincides with the direction of the incoming wind and wave.



(a) Three-dimensional model (b) Foundation configuration

Figure 2. Articulated offshore wind turbine

It's worth noting that the column, ballast and buoyancy tank are the main structures. Their radius, height and thickness parameters directly determine the overall mass and stability state of AOWT. So diameters (D_1、D_2 and D_3), heights (H_1、H_2 and H_3) and thickness (t) are taken as the design variables. On the one hand, the AOWT does not include mooring system, its restoring force is provided by the residual buoyancy completely. On the other hand, the articulated joint bears large pull force and the total weight directly determines the construction cost. So the structure design should consider that the system can provide enough restoring force while minimizing the tension on articulated joint, and at the same time, as much as possible to reduce the weight of structure. Therefore, the objective function is to minimize the mass of the foundation M , minimize the tension of articulated joint F_{joint} and maximize the restoring moment Mgb. Since the motion balance position of the wind turbine is mainly affected by the wind loads[28], in order to meet the requirements of structural stability, an inequality constraint can be defined that the maximum wind pressure of AOWT under the extreme wind speed is less than the restoring moment [29]. As the ballast and buoyancy tank are welded outside the column, another inequality constraint defines that the diameter of the ballast and buoyancy tank should be larger than that of the column. At the same time, considering the definite dimensions of the water depth, the upper and lower height of column, total sum of H_1, H_2 and H_3 is taken as the equation constraint. The multi-objective optimization mathematical model of AOWT is expressed as follows:

$$\begin{aligned}&\min\left\{M, F_{joint}, \text{-}Mgb\right\} = f(D_1, D_2, D_3, H_1, H_2, H_3, t)\\&s.t.\\&\begin{cases}F_{wind} - Mgb \le 0\\ D_1 - D_2 \le 0\\ D_1 - D_3 \le 0\\ H_1 + H_2 + H_3 - 40 = 0\end{cases}\end{aligned} \tag{6}$$

Where D_1, D_2, D_3 respectively represent the diameters of middle column, ballast and buoyancy tank, H_1, H_2, H_3 respectively represent the heights of middle column, ballast and buoyancy tank, t is the thickness, M is the foundation mass, F_{joint} is the tension of articulated joint, Mgb is the restoring moment, F_{wind} denote wind loads of AOWT under the extreme wind speed, which include wind pressure on the tower and blades.

Before the optimization, the range of design variables should be determined first. Refering to the dimensions of articulated tower platform and Spar floating offshore wind turbine, D_1, D_2, D_3 are all in the range from 5 to 30 meters, thickness t can be 0.02 to 0.1 meter. As water depth, the upper and lower heights of the column are determined, H_1, H_2, H_3 all range from 5 to 20 meters. At the same time, the relevant parameter setting in the optimization algorithm should be taken into account.

In general, the population size has a great impact on the population diversity and computational efficiency. It is tested that when the population size is 100, the computational diversity and timeliness can be better balanced. The selection of reference points is based on the Das and Dennis method [30]. In order to improve the population diversity and obtain the offspring with better fitness value, the full reproduction genetic mechanism was adopted, and the probability of crossover and mutation was set as 1.0. Relevant operation parameters of the algorithm are shown in the following table 1.

Table 1. NSGA-III operation parameters

Item	Value
Population size	100
Reference point	21
Crossover probability / binary crossover parameter	1.0 / 20
Mutation probability / polynomial mutation parameter	1.0 / 20
Iterations	100

Through calculation, a group of relatively optimal solutions are obtained, and the Pareto front is shown in figure 3. Figure 4 is the Pareto set, which reflects the variable domain range corresponding to seven decision variables.

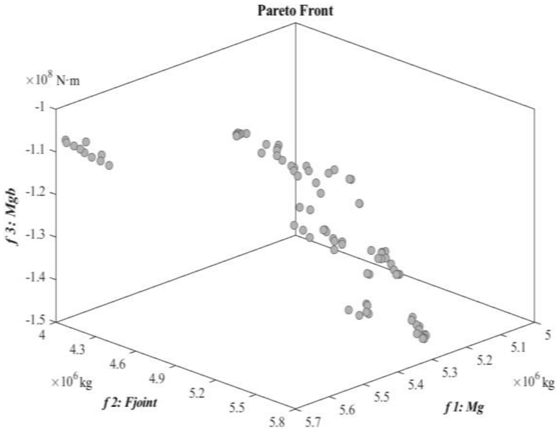


Figure 3. Pareto Front

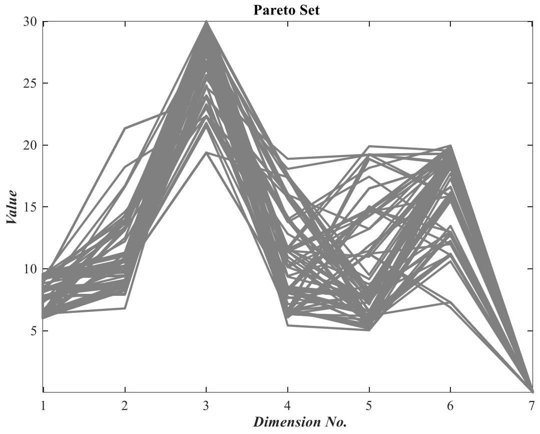


Figure 4. Pareto Set

As can be seen from figure 3, three objectives conflict and influence each other. Most schemes with lower mass have larger tension on joint, otherwise, less tension. While restoring moment is related to difference between them. At the same time, the distribution of Pareto solution on objective function f1 is relatively concentrated. Nevertheless, the distribution on objective function f2 and f3 are reasonable, which not only meet the convergence of the solution in a certain range, but also fully expresse the distribution on the whole objective domain. From figure 4, values of design variables also show good convergence and distribution.

Based on the fuzzy comprehensive evaluation method, the Eq. (5) is adopted to carry out fuzzy optimization on pareto solutions. This papaer mainly focus on three index parameters, which are the foundation mass M , the tension of articulated joint F_{joint} and the restoring moment Mgb. Based on the value range of the objective function in Pareto Front, the objective function is normalized., then T_i can be achieved. Considerding the influence of three index parameters are basically the same, the weight set $L=[1/3, 1/3, 1/3]$ is enabled. Through the quantitative fuzzy evaluation of the 100 population individuals, the final design scheme was obtained according to the scores, and the final scheme is obtained in table 2.

Table 2. AOWT foundation parameters

Parameter	Value	Parameter	Value
Diameter of middle column D_1 /m	6.0	The overall weight /kg	5.24E+06
Diameter of ballast tank D_2 /m	14.0	Center of Gravity	(0,0,31.68)
Diameter of buoyancy tank D_3 /m	25.0	Buoyancy /kg	9.51E+06
Height of middle column H_1 /m	17.0	Center of Buoyancy	(0,0,32.12)
Height of ballast tank H_2 /m	8.0	Pitch inertia / kg ·m^2	1.26 E+10
Height of buoyancy tank H_3 /m	15.0	Initial tension of articulated joint /kN	4.19E+04
Thickness t /m	0.07	Natural frequency of pitch / rad s^{-1}	0.29

4. DYNAMIC SIMULATION RESULTS AND DISCUSSIONS

4.1 Definition of Load Cases

Considering the co-directional operation of wind, wave and current loads, the wave is described by the random wave generated by JONSWAP wave spectrum, and the wave incident is in the positive direction along the X-axis. At the same time, the steady wind and turbulent wind are both simulated. Turbulent wind is simulated by NPD wind spectrum and the incoming flow is considered as steady flow. Considering the first-order wave (1_st wave) force and second-order wave (2_dif and 2_sum) forces, extreme sea state data that happened once a year are adopted for simulation, four different load cases are defined in table 3. These load cases are run for 3600s and specific scenario parameters are shown in table 4.

Table 3. Parameters of load cases

Item	Wave condition	Wind condition
LC_1	1_st wave	Steady
LC_2	1_st+2_dif wave	
LC_3	1_st+2_dif+2_sum wave	
LC_4	1_st+2_dif+2_sum wave	Turbulent

Table 4. Parameters of scenarios

Paremeter	Value
Significant wave height / m	11
Peak period / s	12
Wind speed / m s-1	32
Current speed / m s-1	1.5
Simulated time /s	3600
Time step /s	0.1
Incident direction / deg	0

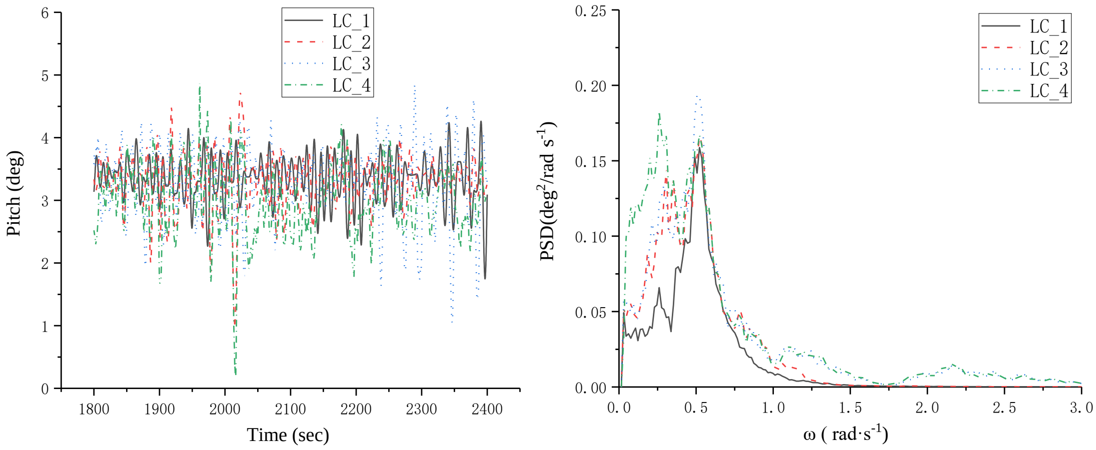
In this paper, the effect of the first order wave force, second-order wave and turbulent wind are all considered on the dynamic response study of AOWT, especially the pitch motion and tension of articulated joint. The data in the stable stage of 30-40min were taken as an example for plotting, and then fourier transform FFT was used to transform the time history results into the frequency domain for comparative analysis. The relevant statistical results are shown in table 5 below.

Table 5. Statistical results in the time domain

Response	Statistic	LC1	LC2	LC3	LC4
Pitch/ °	Average	3.35	3.30	3.31	2.95
	Maximum	4.60	4.80	4.85	4.95
	Minimum	1.75	0.13	0.35	0.04
	standard deviation	0.35	0.45	0.47	0.69
Fjoint/kN	Average	4.42E+04	4.55E+04	4.56E+04	4.57E+04
	Maximum	7.52E+04	8.84E+04	9.46E+04	9.88E+04
	Minimum	1.03E+04	1.94E+04	4.08E+03	9.79E+03
	standard deviation	9.65E+03	9.89E+03	1.05E+04	1.57E+04

4.2 Pitch Motion

A time-history and power spectral density (PSD) sample of pitch motion response is shown in figure 5 below.



(a). Time history curves of pitch (b) Power spectral density of pitch

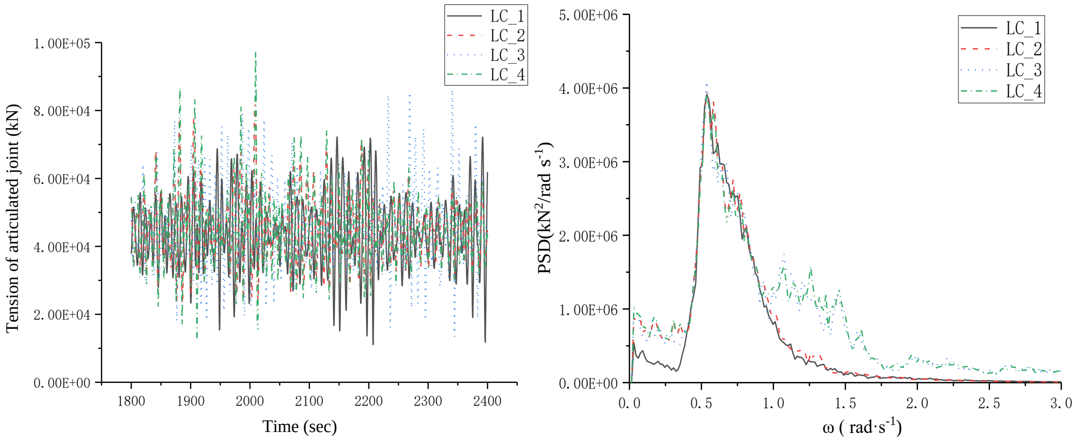
Figure 5. Dynamic response of pitch for AOWT

From the figure 5a and table 5, the average value of pitch keeps about 3.3 degree and the maximum value is no more than 5 degree, which meets the safety threshold value of offshore wind turbine design criteria[31]. The second-order wave loads, including the difference frequency and the sum frequency, has no significant effect on the mean value of the pitch motion response, while the mean value of the pitch motion changes significantly under the turbulent wind. Furthermore, the second-order wave (2_dif and 2_sum) loads immensely change the amplitude of response variation, the standard deviation increases to some extent. Compared with the steady wind scenarios, the low frequency resonance effect caused by turbulent wind further intensifies the variation of response amplitude, and the standard deviation increases significantly as well.

From the response spectral figure 5b, as the wind turbine was parked, the aerodynamic load does not participate in the analysis, there are two main response peaks, the low frequency response near the natural frequency at 0.3rad /s and the wave frequency response at 0.53rad /s. The second-order differential frequency load induces the resonance response at low frequency of pitch motion, and significantly increases the peak value at the natural frequency. While the second-order sum frequency load excites the resonance response at wave frequency, which further increase the corresponding peak value. Compared with the steady wind, the turbulent wind induces larger low-frequency response at low frequencies, the corresponding response peak even exceeds the wave frequency resoponse peak.

4.3 Tension on Articulated Joint

A time-history and power spectral density (PSD) sample of tension on articulated joint is shown in figure 6 below.



(a). Time history curves of tension (b) Power spectral density of tension

Figure 6. Dynamic response of tension on articulated joint

From the figure 6a and table 5, the tension force of articulated joint is mainly dominanted by the wave loads. Among them, the second-order difference frequency load has no obvious effect on the response, while the second-order sum frequency load significantly increases the response standard deviation, and the maximum and minimum values of the response value change obviously. The influence of wind load and turbulent wind on the tension of articulated joint is limited. From the response spectral figure 6b, the position corresponding to response peak is at wave frequency. Although the second-order force and turbulent wind increase the response at low frequency and high frequency to some extent, while they have little effect on the overall response, which is far from the peak value of wave frequency response.

5. CONCLUSIONS

In present work, we put forward a compliant type of articulated foundation offshore wind turbine, which is applied for medium water depth. Considering the safety, stability and economic applicability of structural design, a non-dominated sorting multi-objective genetic algorithm (NSGA-III) based on reference points was adopted to optimize the foundation dimension of AOWT. It overcomes the one-sidedness and singleness of single objective optimization, expands the idea of high-dimensional solution on the basis of double objective optimization, and can conduct comprehensive and effective optimization analysis for complex conditions, especially for three objectives or more problems. Based on the fuzzy optimization method, the fuzzy evaluation analysis of Pareto solution were carried out, and the optimal structural parameters satisfying the evaluation indexes were finally obtained. At the same time, the multi-objective optimization algorithm and calculation process adopted in this paper provide relevant references for the problems with complex design elements and high-dimensional objectives in the future, and provide new ideas for the design of other wind turbine infrastructures.

Moreover, in order to further verify the robustness of AOWT, the dynamic response of the pitch motion as well as tension on articulated joint are all investigated under the severe sea state. Considering the effect of different environemntal factors, including extreme stochastic wave, extreme wind speed and turbulent wind, then contrast and summarize the objective law of different dynamic responses. Through the simulation results, the maximum value of pitch motion and tension on articulated joint both do not exceed the safety threshold [32] , further verifying the safety and effectiveness of the structure design. At the same time, the second-order wave force have little effect on the mean values of different responses, but are more sensitive to amplitude changes. For pitch motion response, the 2_dif wave force induces the resonance at natural frequency and increases the response peak, while the 2_sum wave force further induces the response peak at wave frequency, and the trend getting more pronounced under the action of turbulent wind. For tension response on articulated joint, it is mainly affected by wave load, and the influence of wind load and turbulent wind is limited. At the same time, the effect of second-order wave force on the response is not obvious.

The results in the present work give a clear insight into the physics of wind-wave interaction effect on the dynamic responses of the AOWT system under the severe sea state. Moreover, other simulations, including the cut-in wind speed, rated wind speed and cut-out wind speed etc, should also be conducted to perform a more complete parametric study. Furthermore, the focus of this study is to introduce the optimization method and dynamic response of the AOWT. Thus, for simplicity, the whole system is considered as the rigid body suffering different external excitations and swing around the articulated joint. In addition to numerical simulation, further verification should also be carried out by means of model experiment. In the following works, we are undergoing a basin experiment in Tianjin University, in order to further validate our in-house code and investigate its behaviours which are difficult to be found in the numerical solutions.

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