OPTIMAL DESIGN OF JACKET SUPPORTING STRUCTURES FOR OFFSHORE WIND TURBINES USING ENHANCED COLLIDING BODIES OPTIMIZATION ALGORITHM

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ABSTRACT

Structural optimization of offshore wind turbine structures has become an important issue in the past years due to the noticeable developments in offshore wind industry. However, considering the offshore wind turbines' size and environment, this task is outstandingly difficult. To overcome this barrier, in this paper, a metaheuristic algorithm called Enhanced Colliding Bodies Optimization (ECBO) is utilized to investigate the optimal design of jacket supporting structures for offshore wind turbines when a number of structural constraints, including a frequency constraint, are considered. The algorithm is validated using a design example. The OC4 reference jacket, which has been widely referenced in offshore wind industry, is the considered design example in this paper. The whole steps of this research, including loading, analysis, design, and optimization of the structure, are coded in MATLAB. Both Ultimate Limit States (ULS) and frequency constraints are considered as design constraints in this paper. Huge weight reduction is observed during this optimization problem, indicating the efficiency of the ECBO algorithm and its application in the optimization of offshore wind turbine structures.

Keywords: offshore wind turbines; jacket supporting structures; enhanced colliding bodies optimization; optimal design; structural optimization.

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1. INTRODUCTION

The severe environmental issues that human beings have been encountering in the past years has resulted in replacing the traditional fossil-fuel resources in supplying worldwide energy demands with renewable energies, especially wind energy. Offshore wind industry has been always considered as one of the best options available, mainly due to the existence of numerous appropriate locations for the installment of wind turbines in the marine environments [1].

Bottom-fixed and floating supporting structures are the common structural options in offshore wind industry. In the majority of operating offshore wind turbines throughout the world monopile is being utilized as the main structural system [2]. However, this supporting structure is no longer applicable in deeper regions, since this structural system is not capable of standing harsh environment of such regions. Surprisingly, these regions are more suitable for hosting offshore wind turbines due to their accessibility to stronger wind resources. Thus, frame supporting structures − for instance jacket supporting structures − are on the verge of becoming the most popular supporting structures in offshore wind industry. In fact, these supporting structures could bear the weight of larger wind turbines, which is a noticeable advantage when it comes to designing large offshore wind farms. Tripod and jacket supporting structures are generally considered as the best choices in offshore wind industry. These structural systems have been already employed in oil and gas industry and this acquaintance has been a remarkable help in offshore wind industry [2].

Considering the importance of structural optimization in offshore wind turbine supporting structures, this task has been pursuit by several researchers as follows:

Uys *et* al. explored the optimal design of monopile offshore wind turbine structures by using a zeroth order search algorithm [3]. Thiry *et* al. utilized Genetic Algorithm (GA) in investigating the optimal design of a monopile offshore wind turbine [4]. In their research, Fatigue Limit State (FLS), Ultimate Limit State (ULS) and frequency constraints are considered. Long *et* al. explored the characteristics of tripod and jacket supporting structures for offshore wind turbines under ULS conditions [5]. Long and Moe further extended their results. They consider FLS constraints based on the available design standards [6]. Zwick *et* al. presented a new concept in offshore wind industry, which is called the full-height lattice offshore wind turbine [7]. Furthermore, they utilized an iterative optimization approach in investigating its optimal design under both FLS and ULS constraints. Zwick and Muskulus presented a method for simplifying the assessment of fatigue [8]. Chew *et* al. utilized sequential Quadratic Programming (SQP) optimizer in exploring the optimal design of the Offshore Code Comparison Collaboration Continuation (OC4) reference jacket under ULS, FLS and frequency constraints [9]. Oest *et* al. investigated the optimal design of jacket supporting structures considering FLS, ULS, and frequency constraints [10]. Kaveh and Sabeti explored the optimal design of the OC4 reference jacket when wind and wave loads are considered in-plane [11]. In addition, they investigated the optimal design of offshore monopiles utilizing three different metaheuristic algorithms [12]. Finally, Kaveh and Sabeti explored the optimal design of OC4 reference jacket considering ULS and frequency constraints. To do so, they utilized Colliding Bodies Optimization algorithm [13].

However, this research utilizes a metaheuristic algorithm to investigate the optimal design of jacket supporting structures. In the past years, many such algorithms have been

developed based on the natural phenomena [14-18]. For instance, collision between bodies and the free vibration of a system are two natural phenomena based on which two metaheuristic algorithms have been developed, entitled Colliding Bodies Optimization (CBO) and Vibrating Particle Systems (VPS) algorithms [15]. Simplicity in implementation and less time-consumption in comparison to the other algorithms are considered as the vivid advantages of metaheuristic algorithms [16,18]. Enhanced Colliding Bodies Optimization (ECBO) is a recently developed algorithm based on the physic laws governing the collision between bodies. In fact, this algorithm was developed to enhance the behavior of Colliding Bodies Optimization algorithm [19].

Overall, the main goal of this research is to demonstrate how ECBO algorithm can be utilized in investigating the optimal design of jacket supporting structures for offshore wind turbines. As mentioned, the whole steps of this research, including structural design and analysis, loading, and optimization, are coded in MATLAB. After modeling the structure using Finite Element Method (FEM) principles, the ECBO algorithm is then utilized so that the lightest structural members that satisfy the considered constraints – ULS and frequency constraints – can be found. The efficiency of the utilized algorithm is then investigated employing the OC4 reference jacket. Finally, the outcomes of this research are compared to the original structure, validating the efficiency of the utilized algorithm.

2. CONFIGURATION OF THE OC4 REFERENCE JACKET

As mentioned, frame-supporting structures are currently playing an important role in the offshore wind industry. Generally, these structures consist of two different sections: the lattice section, and the tower. Note that this paper is aimed to investigate the optimal design of the lattice section [2].

The considered design example in this research is the OC4 reference jacket [20-21]. This structure is located at K13 deep-water site in the North Sea, where the mean water level in this site is considered 50 meters above the seabed [22]. Additionally, the well-known 5-MW horizontal axis NREL wind turbine is the utilized turbine in this case. The cut-in and cut-out wind speeds of this wind turbine are 3 m/s and 25 m/s, respectively [23]. The rotor of this wind turbine weighs 1079.1 kN, its nacelle weight is approximately 2354.4 kN, which means that the total weight of the Rotor Nacelle Assembly (RNA) is 3433.5 kN (Fig. 1). The 5-MW NREL wind turbine is placed on the top of a 68-meter long tower, which approximately weighs 2138.58 kN when the weight of its equipment is not considered. The tower and supporting structure in this offshore wind turbine are connected through a transition piece, whose weight is approximately 6474.6 kN. Finally, the weight of the supporting structure in its original design is approximately 6609.17 kN [10].

3. FINITE ELEMENT MODEL

In this paper, Finite Element Method (FEM) is utilized in modelling and analyzing the design example. Each member comprises of two nodes and is modeled as a 3D frame element. It means that each element consists of twelve degrees of freedom. The whole

structure is then modeled in MATLAB using the aforementioned approach. Note that the cross-sectional properties of each element are considered constant throughout the length.

Transition piece in jacket supporting structures is the main character in keeping the whole structure integrated and its role is irrefutable. In this paper, the transition piece is modeled using four elements. One fourth of the total weight of the original transition piece is assigned on each of the mentioned elements [10].

In this research, in addition, the dynamic behavior of the structure is controlled using one frequency constraint. To calculate the frequency of structure, eight extra elements are utilized to model the tower of the wind turbine structure. Additionally, the weight of the Rotor Nacelle Assembly (RNA) is considered as a lumped mass on the top of the tower (Fig. 2). Mass matrix of each element is then calculated using consistent mass matrix. Afterward, the stiffness and mass matrices of the structure can be calculated and the frequencies of the structure could be found using an eigenvalue analysis.
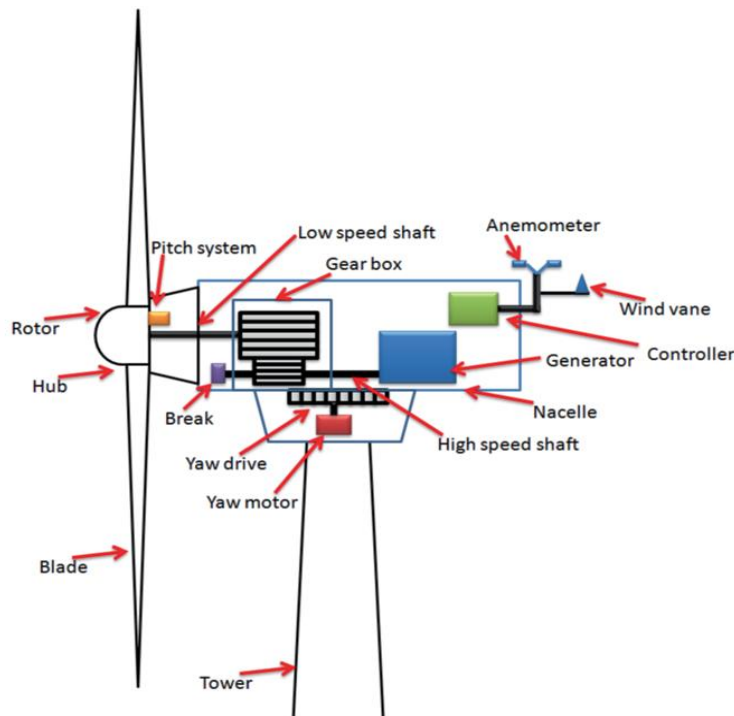

Figure 1. Wind Turbine Components [2]

4. LOADING CONDITIONS

Offshore structures are subject to a number of loading cases. For instance, wave, wind, and currents are the environmental loading cases generally imposed on offshore wind turbine structures (Fig. 3). Thus, in order to analyze and design offshore wind turbines, these environmental loading cases must be accurately calculated. In this paper, environmental loads are assessed based on DNV standard [24-25]. In fact, many load cases must be considered when designing offshore wind turbines; such as regular power production,

extreme weather conditions, shut down etc. Since the extreme weather condition usually results in the worst-case scenario, in this study, this mode is considered as the design condition. Under this condition, it is presumed that the turbine is stopped due to encountering the extreme values of environmental phenomena. In this way, the occurrence of undesired damages attributed to the high wind velocity could be prevented. In addition, in this mode, both ULS and frequency constraints must be satisfied in compliance with standards [24-25].

Generally, the applied loads on offshore wind turbines can be categorized as either permanent or environmental load cases. The weight of both structural and non-structural elements are considered in the former, while wind and wave actions are considered in the latter. In fact, environmental load cases are functions of metocean data − such as wave height, and wind velocity. It means that their values would differ in different sites [2]. Nevertheless, in this research, wind and wave loadings are the environmental load cases considered. These load cases are briefly described here:
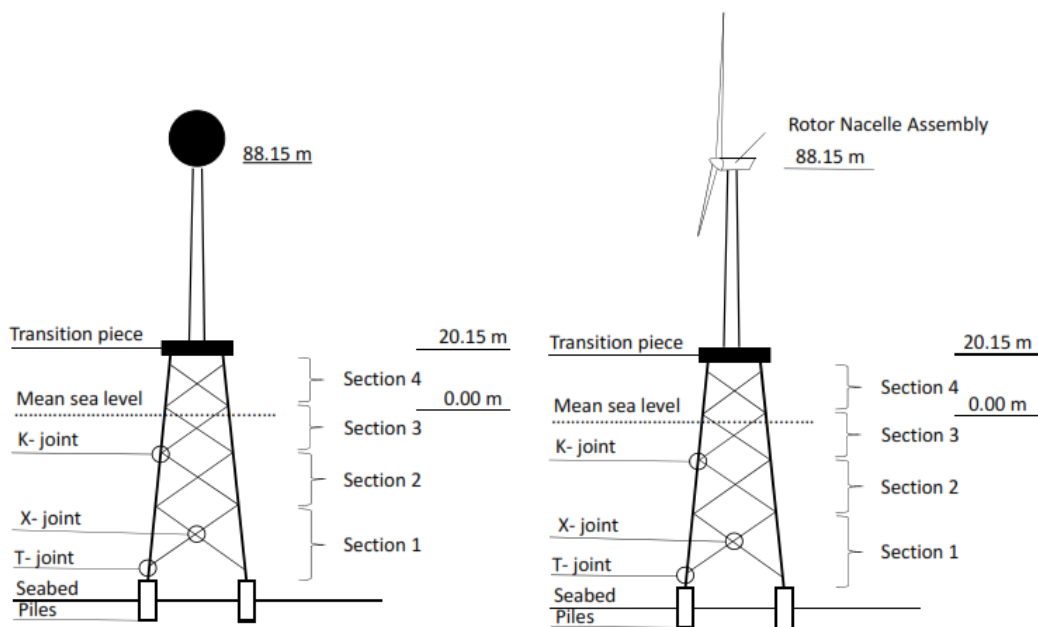

Figure 2. The OC4 reference jacket structure and the considered model (lumped mass)

4.1 Wave loading

In the literature, Morrison formula has been widely utilized in the assessment of wave action on slender structures [2]. However, this formula is solely applicable to the cases where the diameter of structures is noticeably smaller than the wavelength [2]. According to this equation, hydrodynamic load on a unit length of a slender structure consists of drag and inertia terms, which can be written as follows:

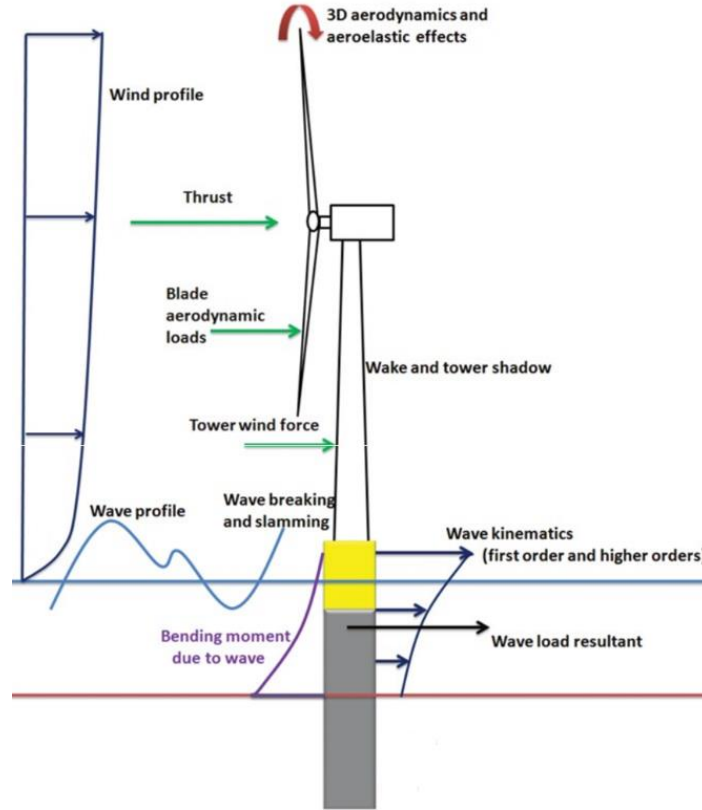$$dF = dF_m + dF_d = \frac{C_m \pi \rho D^2}{4} \dot{u}_w dz + \frac{C_d \rho D}{2} |u_w| u_w dz \qquad (1)$$

Figure 3. Aero-hydro dynamic loads applying on an offshore wind system [2]

In Eq. (1), dF_m is the inertia force (N/m), dF_d is the drag force (N/m), C_m is the inertia coefficient, C_d is the drag coefficient, D is the element diameter (m), ρ is the mass density of seawater (kg/m^3), u_w is the horizontal velocity of the water particle (m/s) and $\dot{u}_w$ is the horizontal acceleration of water particle (m^2/s). Drag and inertia coefficients are calculated based on Keulegan-Carpenter number, relative roughness and Reynolds number. These values are considered 0.7 and 2 in this research, respectively. Additionally, in this research, Airy Wave Theory (Linear Wave Theory) is utilized for the acceleration and velocity of the water particles to be assessed [2].

It should be noted that in this research, in order to assess hydrodynamic load on oblique members, some geometrical manipulation are employed so that the normal velocity and acceleration of water particles to the axis of each inclined member can be found. Afterward, Morrison formula is utilized and the normal wave force to the axis of each element can be calculated.

4.2 Wind loading

4.2.1 Wind force on tower

According to DNV code, the effect of wind on the tower of offshore wind turbines could be calculated as follows [25-26]:

$$F = \frac{1}{2} \times \rho_a \times C_S \times S \times U^2 \tag{2}$$

In Eq. (2), ρ_a is the air density (kg/m^3), C_S is the shape coefficient, S is the projected area of the member normal to the direction of the force (m^2) and U is the wind velocity (m/s). In this research, shape coefficient is considered 0.15. The required parameters in the calculation of the wind effect are described here [25]:

$$C = 5.73 \times 10^{-2} \times \sqrt{1 + 0.15 \times U_0} \tag{3}$$

$$U(T, z) = U_0 \times \left\{ 1 + C \times \ln\left(\frac{z}{h}\right) \right\} \times \left\{ 1 - 0.41 \times I_U \times \ln\left(\frac{T}{T_0}\right) \right\} \tag{4}$$

$$I_U = 0.06 \times (1 + 0.043 \times U_0) \times \left(\frac{z}{h}\right)^{-0.22} \tag{5}$$

In the abovementioned formulas, U_0 is the 1-hour wind mean speed at 10 meter height (m/s), h and T_0 are considered 10 meters 3600 seconds, respectively.

4.3.2 Wind force on rotor and nacelle assembly

In order to accurately calculate the wind effect on Rotor and Nacelle Assembly (RNA), a comprehensive study is needed that considers 3D aero-servo-elastic analysis. However, such analysis is not simply feasible. Thus, in this research, the effect of wind on the RNA is calculated based on a scaling relationship presented by Manwell *et* al. [27]. Referring to this relationship, the wind effect on any arbitrary wind turbine could be calculated based on a known wind turbine's characteristics as follows [28]:

$$\frac{T_1}{T_2} = \left(\frac{R_1}{R_2}\right)^2 \tag{6}$$

$$\frac{M_1}{M_2} = \left(\frac{R_1}{R_2}\right)^3 \tag{7}$$

In Eq. (6) and Eq. (7), R_1/R_2, T, and M are the ration of rotor diameters, aerodynamic thrust and aerodynamic moment, respectively.

Therefore, based on what is presented in Leite [29], in this research, aerodynamic thrust and moment for the 5-MW NREL wind turbine is readily determined. Note that using this relationship results in an acceptable approximation for the initial steps of designing offshore wind turbines. However, as mentioned, more detailed analyses are required in the next steps.

4.3 Load combinations

Following load combinations must be considered in the evaluation of ULS constraints in offshore wind turbines based on DNV 2014 [25]:

First Load Combination: 1.25*dead load + 0.7*wind load + 0.7*wave load
Second Load Combination: 1*dead load + 1.35*wind load + 1.35*wave load.

Note that dead load in the abovementioned combinations contains of self-weight of the whole structure including tower, supporting structure and the weight of wind turbine. Additionally, wind load comprises of the wind actions applied on tower, supporting structure, and turbine

5. THE STRUCTURAL OPTIMIZATION PROBLEM

The main goal of structural optimization is to find a set of design variables $(X = [x_1, x_2, x_3, x_4, \ldots, x_n])$, which are chosen within a predefined interval $(x_{imin} \leq x_i \leq x_{imax})$, so that the objective function is minimized when it is subjected to a number of constraints $(g_i(X))$. In the abovementioned formulas, X is the vector of design variables with n unknowns and g_i is the ith constraint from m inequality constraints. The well-known penalty approach is utilized in this research for constraint handling [14]. The utilized penalty function in this research is described below:

$$f_{penalty}(X) = \left(1 + \varepsilon_1 \sum_{i=1}^{m} \max\left(0, g_i(X)\right)\right)^{\varepsilon_2} \tag{8}$$

In Eq. (8), $Mer(X)$ is the merit function, $f(x)$ is the objective function and ε_1 and ε_2 are the parameters which control the balance between exploration and exploitation rates in the algorithm. These values are taken one and three in this study, respectively.

5.1 Design variables

The diameter and thickness of each member of the jacket supporting structure are the design variables in this optimization problem. The members of this structure are categorized in ten different groups (Fig. 4); hence, the design variable vector of this problem comprises of 20 entities. The intervals from which thickness and diameter of each element are chosen in this study are from 0.01m to 0.1m and from 0.1m to 5m, respectively.

$$X = [D_1, D_2, \ldots, D_{10}, t_1, t_2, \ldots, t_{10}] \tag{9}$$

5.2 Design constraints

As mentioned, both ULS and frequency constraints are considered in the investigation of the optimal design of jacket supporting structures. To control the dynamic behavior of offshore wind turbines, their frequency must be monitored and limited within a predefined interval so that the occurrence of undesired phenomena, such as dynamic resonance, could be

prevented. In this research, the first frequency of the structure is calculated and restricted between 0.22 and 0.31 Hz, respectively [10].

In addition, ULS constraint (Buckling Failure) is considered in this research based on Eurocode 3 [30]. Each element, e, except the elements modelling the tower and transition piece, must be designed based on this constraint. These elements must satisfy the following constraints under the combination of bending and axial compression:

$$B_e = \frac{N_{ED}}{\chi_y N_{RK}/\gamma_{M1}} + k_{yy} \frac{M_{y,ED}}{\chi_{LT} M_{y,RK}/\gamma_{M1}} + k_{yz} \frac{M_{z,ED}}{M_{z,RK}/\gamma_{M1}} \tag{10}$$

$$G_e = \frac{N_{ED}}{\chi_z N_{RK}/\gamma_{M1}} + k_{zy} \frac{M_{y,ED}}{\chi_{LT} M_{y,RK}/\gamma_{M1}} + k_{zz} \frac{M_{z,ED}}{M_{z,RK}/\gamma_{M1}} \tag{11}$$
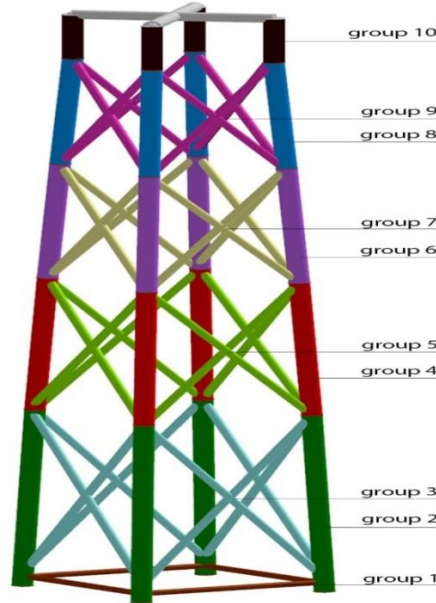

Figure 4. Design grouping (Gray elements not being optimized)

In Eq. (10) and Eq. (11), N_{ED}, $M_{y,ED}$, and $M_{z,ED}$ are the design compression force and maximum moments about the local y-y and z-z axis, respectively. N_{RK} ,$M_{y,RK}$, and $M_{z,RK}$ are the resistance force and moments of the critical cross-section, respectively. Furthermore, γ_{M1} is a partial safety factor for the global stability, which is considered 1.2 in this research according to IEC [31]. χ_{LT} is the reduction factor which considers the effect of lateral torsional buckling. however, this coefficient is considered as unity in this research since the utilized elements are circular hollow members. k_{yy}, k_{yz} , k_{zy}, and k_{zz} are interaction factors, which are calculated based on [30]. χ_y, and χ_z, named reduction factors, which take flexural buckling into account, can be calculated as follows:

$$\chi_y = \chi_z = \min\left[\frac{1}{\Phi + \sqrt{\Phi^2 - \bar{\lambda}^2}}, 1\right] \tag{12}$$

$$\Phi = 0.5\left[1 + \alpha(\bar{\lambda} - 0.2) + \bar{\lambda}^2\right] \tag{13}$$

$$\bar{\lambda} = \sqrt{\frac{Af_y}{N_{cr}}} \tag{14}$$

$$N_{cr} = \frac{\pi^2 EI}{L^2} \tag{15}$$

In abovementioned formulas, $\bar{\lambda}$ is non-dimensional slenderness, N_{cr} is the Euler critical force, L is the length of the considered column, and f_y and E are the yield stress and the Young's modulus of the utilized material, respectively. As another constraint, to prevent the local instability failure in the elements of the structure, the ratio of diameter over thickness in all elements is restricted to 59.4 [30].

5.3 Objective Function

In this optimization problem, the objective function is the supporting structure weight, which can be written as follows:

$$f(X) = \sum_{i=1}^{n} \rho g V_i = \sum_{i=1}^{n} \rho g A_i L_i = \sum_{i=1}^{n} \rho g (\pi D_i t_i L_i) \tag{16}$$

6. ENHANCED COLLIDING BODIES OPTIMIZATION ALGORITHM

Enhanced Colliding Bodies Optimization (ECBO) is the improved version of Colliding Bodies Optimization (CBO) algorithm, which has been recently developed based on momentum and energy conservation laws in one-dimensional collision between bodies. To improve the CBO algorithm, ECBO utilizes a memory in order to save some historically best CBs, which results in obtaining better solutions while consuming less time. Additionally, a mechanism is defined to randomly change some components of CBs to afford a chance for the CBs to escape from the local minima and prevent probable premature convergence. This algorithm is mentioned as follows [19]:

Level 1: Initialization

Step 1: The initial positions of all colliding bodies are randomly determined within the search space.

Level 2: Search

Step 1: Each CB needs to be assigned a mass value based on following equation.

$$m_k = \frac{\frac{1}{fit(k)}}{\sum_{i=1}^{n}\frac{1}{fit(i)}} \qquad k = 1,2,\dots,2n \tag{17}$$

In Eq. (17), fit(i) is the value of objective function for the ith agent. It can be perceived

that larger and smaller masses are carried by better and worse CBs, respectively.

Step 2: Colliding Memory (CM) is then used to save a number of best-so-far vectors and their related mass and objective function values. Solution vectors that are saved in CM are added to the population, and, consequently, the same number of the current worst CBs are discharged from the population. Afterward, CBs are sorted based on their corresponding objective function values in an increasing order.

Step 3: CBs are divided into two equal groups: (i) stationary group, and (ii) moving group.

Step 4: The velocity of moving CBs before collision is calculated in this step using Eq. 18. Note that the velocity of stationary CBs before collision is zero.

$$v_i = x_i - x_{i-n} \quad i = n + 1, n + 2, ... , 2n \tag{18}$$

Step 5: The velocities of both stationary and moving bodies after collision are then calculated using Eq. 19. and 20.

$$v'_i = \frac{(m_{i+n} + \varepsilon m_{i+n})v_{i+n}}{m_i + m_{i+n}} \qquad i = 1,2, ... , n \tag{19}$$

$$v'_i = \frac{(m_i - \varepsilon m_{i-n})v_i}{m_i + m_{i+n}} \qquad i = n + 1, n + 2, ... , 2n \tag{20}$$

In ECBO algorithm, coefficient of restitution (ε) is utilized so that the rate of exploration and exploitation could be controlled during optimization. This ratio is defined as follows:

$$\varepsilon = 1 - \frac{iter}{iter_{max}} \tag{21}$$

Step 6: Eq. 22 and 23 determine the new position of each CB after collision.

$$x_i^{new} = x_i + rand \circ v'_i \qquad i = 1,2, ... , n \tag{22}$$

$$x_i^{new} = x_{i-n} + rand \circ v'_i \qquad i = n + 1, n + 2, ... , 2n \tag{23}$$

Step 7: In order to escape from local minima, a parameter called Pro is defined within (0,1) which specifies whether a component of each CB must be changed or not. For each colliding body, Pro is compared with rn_i (i=1,2,…, n), which is a random number uniformly distributed within (0,1). If $rn_i <$ Pro, one design variable of ith CB is selected in random and its value is regenerated using following formula:

$$x_{ij} = x_{i, min} + random \circ (x_{j, max} - x_{j, min}) \tag{24}$$

where x_{ij} is the jth design variable of the ith CB, and $x_{j,max}$ and $x_{j,min}$ are the upper and lower bounds of the jth variable, respectively. To protect the structure of CBs, only one dimension is altered. Note that In Eq. (22) Eq. (23), and Eq. (24), the sign "$\circ$" denotes an element by element multiplication.

Level 3: Terminal Condition

Step 1: The optimization process is stopped when a predefined maximum evaluation number such as the maximum number of iterations is reached.

7. RESULTS

This study is aimed to demonstrate how a metaheuristic algorithm can be utilized in the structural optimization of jacket supporting structures for offshore wind turbines. The OC4 reference jacket is the design example that validates the results of this research. As mentioned, the structure is firstly modeled in MATLAB (Fig. 5) using FEM principles and its optimal design is then investigated using Enhanced Colliding Bodies Optimization. Wind and wave effects are the considered environmental load cases, which are assessed based on DNV standard. The characteristics required for the quantification of the wave and wind actions are provided in the Table 1. The structural properties of the utilized steel in the jacket supporting structure are ($f_y = 355$ MPa, $E = 2 \times 10^5$ MPa, $\rho = 7885$ kg/m^3). The mass density of seawater is considered ($\rho = 1025$ kg/m^3). The mass density of air is considered as ($\rho = 1.225$ kg/m^3) when assessing wind load.

Table 1: Simplified load cases used in the case study [32]

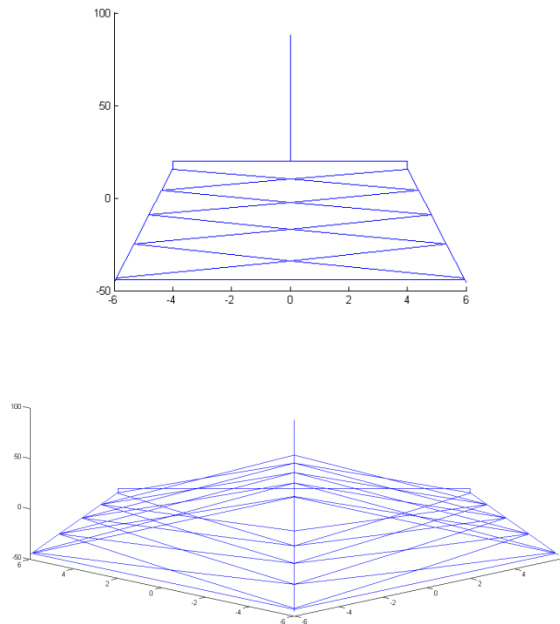|		
	Significant wave height (m)	9.4
Wave	Wave period (s)	13.7
	Water depth (m)	50
Wind	1-hour mean wind speed at hub height (m/s)	42.73

Figure 5. The 3D structure model in MATLAB

7.1 Hydrodynamic loading

Note that in this research, it is assumed that both drag and inertia terms of Morrison equation simultaneously take place. Additionally, the hydrodynamic loading is assessed in a constant phase angle, which is considered as zero. The wave load in both ends of each member are calculated. This load is imposed on the members as a uniformly distributed load by averaging the hydrodynamic loads acting on the starting and ending nodes of each member.

7.2 Aerodynamic loading

Aerodynamic load acting on the structural members of the design example is calculated using the same methodology as hydrodynamic loads. It means that the wind load is considered as a uniformly distributed load on each element. Additionally, the thrust and aerodynamic moments acting on the RNA in the stopped mode are approximately calculated using what is presented in Leite [29] and Gencturk et al. [28] as follows (Table 2):

Table 2: Aerodynamic forces in the structure

Total Force (kN)	696.96
Total Moment (kN.m)	74.30

7.3 Final results

In this study, the optimal design of the OC4 reference jacket supporting structure is investigated using Enhanced Colliding Bodies Optimization (ECBO) algorithm. This optimization problem deals with 20 design variables, which are the diameters and thicknesses of supporting structure elements. These elements are categorized in ten design groups. Twenty colliding bodies in 500 iterations are utilized in the investigation of the solution to this engineering problem. The outcomes of this research, which are presented in Table 3, are compared with the original structure and the results reported in Kaveh and Sabeti [11], where ECBO is utilized in the investigation of the optimal design of the same example, yet, with different methodology. The weight of supporting structure during the optimization process in each iteration and its corresponding penalized objective function are depicted in Fig. 6 and Fig. 7, respectively. In addition, the iteration history of the considered frequency constraint is shown in Fig. 8.
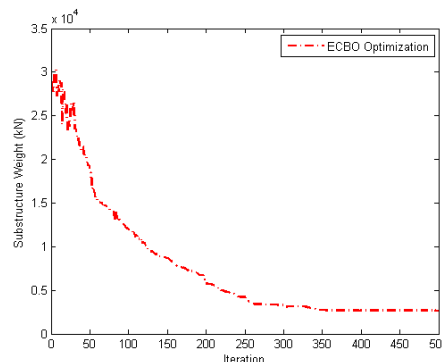

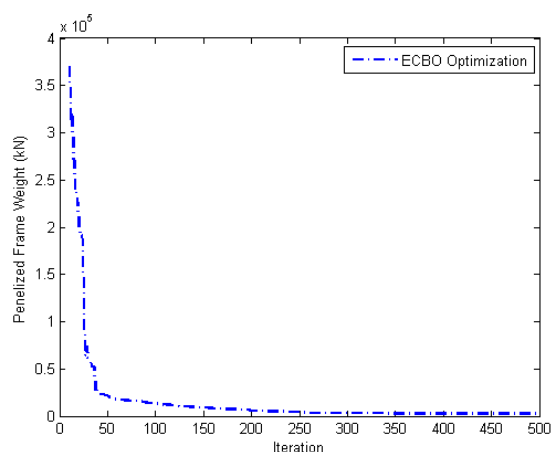Figure 6. Supporting structure weight during optimization

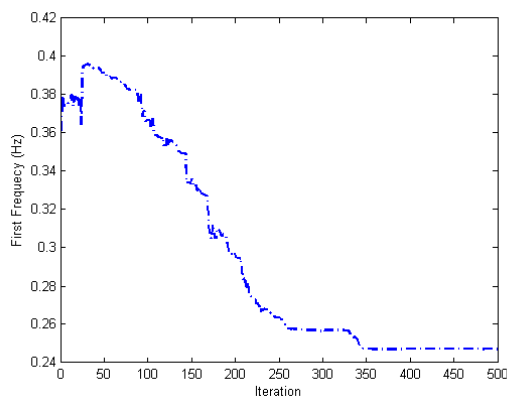Figure 7. Convergence curve during optimization (Iteration 10-500)

Figure 8. The iteration history of the first frequency of structure during optimization

8. CONCLUDING REMARKS

The structural optimization of the offshore wind turbine structures is of the most complex engineering tasks. The remarkable dependency between the intensity of environmental load cases and the utilized cross-sections in members further aggravates this difficulty. However, to overcome this barrier, this optimization problem is handled in this study using a metaheuristic algorithm named as Enhanced Colliding Bodies Optimization (ECBO) algorithm. The OC4 reference jacket is additionally employed in this study to validate the efficiency of the proposed algorithm. The whole steps of this research are conducted using MATLAB. The structure is thoroughly modeled using Finite Element Method (FEM) principles and its optimal design is then pursuit under Ultimate Limit State (ULS) and frequency constraints. A scaling approximation presented by Manwell *et* al. is utilized in the calculation of the wind effect on the Rotor Nacelle Assembly (RNA) [27-28]. Additionally, hydrodynamic load effect on the supporting structure elements is calculated based on Morrison equation. Since the structure comprises of both horizontal and oblique members,

in order to calculate the wave loading on the structural members, the normal water particle kinematics – water particle acceleration and velocity – to the member axis of all elements are firstly assessed using geometrical manipulations. Afterward, employing Morrison equation, the normal wave load to the member axis of each element is calculated. ECBO algorithm is then deployed attempting to explore the optimal design of the jacket supporting structure under extreme weather condition. Huge weight reduction is observed in the optimization process while all the constraints, including the frequency one, are satisfied.

Table 3: Optimum design variables using ECBO algorithm

Design Variable	Original Supporting structure	Kaveh and Sabeti [11]	This Study
D_1 (m)	0.8	0.7364	0.5434
D_2 (m)	1.2	1.3914	1.1361
D_3 (m)	0.8	0.6176	0.5036
D_4 (m)	1.2	1.2166	1.1153
D_5 (m)	0.8	0.6876	0.3883
D_6 (m)	1.2	0.9504	1.0575
D_7 (m)	0.8	0.7690	0.4967
D_8 (m)	1.2	0.8646	0.9552
D_9 (m)	0.8	0.7953	0.6145
D_{10} (m)	1.2	0.5547	0.5268
t_1 (m)	0.02	0.0132	0.0103
t_2 (m)	0.05	0.0236	0.0241
t_3 (m)	0.02	0.0127	0.0103
t_4 (m)	0.035	0.0223	0.0299
t_5 (m)	0.02	0.0116	0.0141
t_6 (m)	0.035	0.0194	0.0212
t_7 (m)	0.02	0.0130	0.0157
t_8 (m)	0.035	0.0216	0.0197
t_9 (m)	0.02	0.0135	0.0151
t_{10} (m)	0.04	0.0643	0.0153
First Frequency (Hz)		0.2412	0.2470

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