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To cite this article: Rad Haghi et al 2014 J. Phys.: Conf. Ser. 555 012046

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# **Integrated Multidisciplinary Constrained Optimization of Offshore Support Structures**

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Abstract. In the current offshore wind turbine support structure design method, the tower and foundation, which form the support structure are designed separately by the turbine and foundation designer. This method yields a suboptimal design and it results in a heavy, overdesigned and expensive support structure. This paper presents an integrated multidisciplinary approach to design the tower and foundation simultaneously. Aerodynamics, hydrodynamics, structure and soil mechanics are the modeled disciplines to capture the full dynamic behavior of the foundation and tower under different environmental conditions. The objective function to be minimized is the mass of the support structure. The model includes various design constraints: local and global buckling, modal frequencies, and fatigue damage along different stations of the structure. To show the usefulness of the method, an existing SWT-3.6-107 offshore wind turbine where its tower and foundation are designed separately is used as a case study. The result of the integrated multidisciplinary design optimization shows 12.1% reduction in the mass of the support structure, while satisfying all the design constraints.

#### 1. Introduction

Offshore wind energy is a growing industry, with thousands of megawatts yearly installation worldwide to enable the transition from a society dependent on fossil fuels to renewable energy. Offshore wind turbines benefit from higher and steadier winds at sea, but the required marinization makes them more expensive than onshore wind turbines.

Among several different marinization cost elements, the support structure (foundation and tower) has the highest cost share [1]. Currently, the most widely used support structure is a tubular tower that is connected through a transition piece to a monopile, and it is a suitable concept for water depths of up to 40 m [2]. The common industrial practice of designing such a concept is to optimize the foundation (monopile and transition piece) and tower independently by the foundation and wind turbine designer. Few sequential iterations between the wind turbine and the foundation designer are used to achieve a sound design and meet the integrated frequency-band requirement of the support structure [3].

Obviously, such an isolated approach results in a suboptimal design for both the tower and foundation, and it does not offer the required cost reduction needed to make offshore wind energy competitive with traditional energy resources. An integrated approach where both the tower

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and foundation are designed at once can yield a better design and thereby impact the cost of the support structure more positively.

Previous studies show the advantages of the integrated design with either limited design constraints or disciplines [4, 5, 6, 7, 8, 9, 10, 11]. The work presented herein addresses some of the shortcomings of the previous works by developing an integrated design method with all the relevant disciplines (structure, aerodynamics, hydrodynamics and soil mechanics) and design constraints (buckling, fatigue damage and natural frequency) involved. Two different optimization algorithms are used to enhance the speed and convergence rate.

This integrated methodology is used to redesign an existing SWT-3.6-107 wind turbine support structure of a real offshore wind park where both its tower and foundation are designed separately. Optimization results are compared with this initial SWT-3.6-107 support structure to investigate the benefits of the integrated design and its influence on the design constraints and objective function. Because of data confidentially, results are presented in an abstract and normalized form, but still clear enough to judge the effectiveness of the method.

The reminder of the paper is organized as follow. First, the integrated design methodology of the support structure is described. Then, the optimization problem formulation is presented. Next, results of the integrated design methodology are compared with the initial design. Finally, recommendation and conclusion are presented.

# 2. Integrated design methodology

This section presents different disciplines that play an important role in modeling the support structure. These different disciplines are coupled to enable integrated multidisciplinary simulation of the support structure and provide the objective function and design constraints needed for the optimizer. A MATLAB script is used to automate data and process flow, and prevent the manual intervention of the designer during the optimization iterations [12]. Figure 1 shows the integration and connectivity of different computational models.



Figure 1: Optimization problem flowchart showing the building blocks of the integrated framework and their interaction

## 2.1. Structural model

The support structure is modeled by Timoshenko beam elements [13]. Using this formulation, the structure is discretized along the height into different sections. Each section has a constant thickness, and it has either a tapered or cylindrical shape. In this way, each section is represented as an element with two nodes as depicted in Figure 2. Structural properties of the support structure are obtained using an analytical model presented by [14].



Figure 2: A schematic drawing of the support structure (left) and representative finite element model with lateral springs under the mud line where they represents the soil stiffness (right)

## 2.2. Soil model

The soil is modeled as a series of linear lateral springs [15]. These springs represent the stiffness of the soil at different sections as depicted in Figure 2. These sectional soil stiffness matrices are added to the structural stiffness matrix of the monopile below the mulline to form a unified stiffness matrix of both the soil and structure [16]. A linear interpolation scheme is performed to obtain the soil stiffness on the exact location of the finite element nodes of the structure.

## 2.3. Aerodynamic model

A blade element momentum model is developed to account for aerodynamic loads that the rotor experiences during operation. The model includes hub and tip loss add-on, as well as dynamic stall and dynamic inflow correction [17]. These aerodynamic loads (thrust and bending moment) are applied as nodal forces and moments at the tower top nodes. Using this model, all of the IEC61400-3 [18] prescribed load cases such as power production (DLC1.2) to evaluate fatigue loads, and normal shut down combined by an extreme operating gust (DLC4.2) to evaluate ultimate loads are considered in the design. For this purpose, the relevant 3D turbulent wind files are generated using TurbSim that is a free and open source code developed by NREL [19].

# 2.4. Hydromechanic model

Several different methods exist to compute the velocity and acceleration profile of waves [20]. To obtain these wave kinematics needed to calculate the loads on the monopile, irregular waves are approximated in this work with classical linear (Airy) wave theory [21]. This method only provides wave kinematics up to the mean water level, and Wheeler stretching is used to redistribute the velocity and acceleration profiles up to the actual sea surface [22].

To simulate the dynamic response due to the hydrodynamic forces acting on the monopile, time-series of the hydrodynamic loads for each section are realized using the empirical Morison equation [23]. In the Morison equation, the drag and inertia forces due to horizontal fluid particle velocities and accelerations, U and  $\dot{U}$  respectively, are added together to estimate the total in-line wave force:

$$f_{Morison} = f_D + f_I = \frac{1}{2}\rho C_d D |U| U + \rho C_m \frac{\pi D^2}{4} \dot{U}$$
(1)

here  $\rho$  and D represent the water density and structural diameter, respectively. The magnitude of the force components depends on a proper selection of appropriate values for the added inertia and drag force coefficients,  $C_m$  and  $C_d$ , and because of data confidentiality are not presented here.

#### 3. Optimization problem formulation

The aim of this study is to minimize the support structure mass using the integrated design methodology and compare that with the reference SWT-3.6-107 design where the foundation and tower are optimized separately by the foundation and wind turbine designer. This mass minimization procedure is subjected to fatigue damage, local and global buckling, and natural frequency as the design constraints. The design variables are the wall thicknesses of the sections, **t**. The optimization problem can be expressed mathematically as:

where in (2),  $m(\mathbf{t})$  is the mass of the support structure and  $\mathbf{g}(\mathbf{t})$  is the vector of constraints.

#### 3.1. Design variable

The design variables are the wall thickness of the section. As mentioned earlier, the support structure consists of a number of sections where each section has a constant wall thickness along its length. From Figure 2, it is observable that there is an overlap between transition piece and monopile. For that overlap region the thicknesses from monpile and transition piece are summed up and one element with the larger thickness is considered. All these design variables are continuous and differentiable. The vector of the design variables is formed as:

$$\mathbf{t} = \begin{bmatrix} t_1 & t_2 & t_3 & \dots & t_n \end{bmatrix}^{\mathrm{T}}$$
(3)

The design variable range is limited with upper and lower bounds, i.e.  $L_l$  and  $U_l$ . These values are  $\pm 300\%$  of the actual wall thickness of the SWT-3.6-107 wind turbine. Other geometrical parameters of the support structure such as diameter and penetration depth are kept the same as the initial design to enable a fair comparison.

$$\mathbf{L}_{\mathbf{l}} \le \mathbf{t} \le \mathbf{U}_{\mathbf{l}} \tag{4}$$

Journal of Physics: Conference Series 555 (2014) 012046

### 3.2. Objective function

Each section's mass is calculated first, and they are summed up next to calculate the total support structure mass, which is equal to the objective function to be minimized. The total mass can be formulated as:

$$m(\mathbf{t}) = \pi \rho \sum_{i=1}^{n} \frac{D_i^2 - (D_i - 2t_i)^2 + D_{i+1}^2 - (D_{i+1} - 2t_i)^2}{8} l_i$$
(5)

where

$m(\mathbf{t})$	: Mass	of	support	structure	[kg]
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- n : Number of sections [-]
- $\rho$  : Used material density [kg/m<sup>3</sup>]
- $D_i$  : Top diameter of section [m]
- $D_{i+1}$  : Bottom diameter of section [m]
- $t_i$  : Wall thickness of section[m]
- $l_i$  : Length of section[m]

Each section's mass is a function of the wall thickness, therefore by changing the wall thicknesses (the design variables) the total mass varies too.

#### 3.3. Design constraints

To end up with a feasible and realistic design, several design constraints are introduced to bound the design space as explained next.

#### 3.3.1. First integrated natural frequency

The first natural frequency is derived from solving an eigenvalue problem based on the finite element model of the support structure as:

$$(\mathbf{K}_{global} - \lambda \mathbf{M})\mathbf{x} = 0$$
(6)  
$$\lambda = \omega_n^2$$
  
$$\mathbf{K}_{global} = \mathbf{K} + \mathbf{K}_{\mathbf{g}}$$

where  $\mathbf{K}_{global}$  is the global stiffness matrix,  $\mathbf{K}$  is the structural stiffness matrix,  $\mathbf{K}_{\mathbf{g}}$  is the soil stiffness matrix,  $\mathbf{M}$  is the mass matrix,  $\lambda$  is an eigenvalue,  $\mathbf{x}$  is an eigenvector and  $\omega_n$  is a natural frequency of the structure. Solving this eigenvalue problem yields  $\omega$  and  $\mathbf{x}$  which represent the eigenfrequencies and mode shapes of the structure respectively [24].

Similar to the SWT-3.6-107 wind turbine, the first natural frequency is bounded with a lower  $(f_l)$  and upper bound  $(f_u)$  as:

$$f_l \le f_{nat} \le f_u \tag{7}$$

therefore, (7) can be formulated as inequality constraints as following.

$$g_1(\mathbf{t}) = f_l - f_{nat} \le 0 \tag{8}$$

$$g_2(\mathbf{t}) = f_{nat} - f_u \le 0 \tag{9}$$

#### 3.3.2. Buckling constraint

Two kind of bucklings are considered in this study, the local and global buckling. The local buckling is calculated based on the design code EN1993-1-6-2007 [25], and global buckling is calculated using the developed finite element model of the support structure.

## **Global buckling**

The eigenvalue problem to calculate global buckling can be formulated as following:

$$(\mathbf{K} - \lambda \mathbf{K}_{\mathbf{G}})\mathbf{x} = 0 \tag{10}$$

where in (10)  $\lambda$  is the multiplication of the reference load to make the buckling happen and **x** is the buckling mode. The solution of (10),  $\lambda$ , is a multiplier for the reference load *P*. It means that global buckling happens when the applied load is equal to  $\lambda P$  so:

$$1 - \lambda < 0$$

therefore,

$$g_3(\mathbf{t}) = 1 - \lambda \le 0 \tag{11}$$

### Local buckling

The local buckling happens when the applied stress on a section is more than the stress capacity of the section. This means a buckling unity check for every section that should be smaller than 1 to have structural stability. This unity check along the support structure can be formulated as:

$$b_{loc_i}(\text{Applied stress}, \mathbf{t}) = \frac{\text{Applied stress}}{\text{Stress capacity}}$$
$$\mathbf{b}_{loc} = \begin{bmatrix} b_{loc_1} & b_{loc_2} & b_{loc_3} & \dots & b_{loc_n} \end{bmatrix}^{\text{T}}$$
$$\mathbf{g}_4(\mathbf{t}) = \mathbf{b}_{loc} - \mathbf{1} \le 0$$
(12)

therefore

 $\mathbf{SO}$ 

where  $\mathbf{g}_4(\mathbf{t})$  is the local buckling constraint vector for the optimization problem.

#### 3.3.3. Fatigue constraint

One of the methods to calculate the fatigue damage of structural members is the S-N curve [26]. Fatigue properties are determined by the slope of the S-N curves, and the location of the intercept with the abscissa. A slope of 4 and an intercept of 110 MPa is used to characterize the support structure steel in this work.

To use these curves, the applied stress on the structure needs to be calculated. Knowing this value and using the S-N cure, one can obtain the number of cycles that the structure can sustain under this stress. Since, only one value for stress is accepted, an equivalent stress level based on von Mises theory is calculated [26].

Fatigue damage calculation is done using rain flow cycle counting of the stress time-signals and applying Palmgren-Miner's rule [27].

$$d = \sum \frac{n_i}{N_i} \tag{13}$$

where d is the total fatigue damage,  $n_i$  is the actual number of cycle, and  $N_i$  the total number of cycle for a given stress level.

For this work, the stress concentration factors are extracted from DNV-OS-J-101 design standard [28] in the locations that the support structure sections are welded to each other. The fatigue damage is a vector with the same size as the number of sections. This vector represents the damage along the support structure as:

$$\mathbf{d} = \begin{bmatrix} d_1 & d_2 & \dots & d_n \end{bmatrix}^{\mathrm{T}}$$

In order to keep the structure stable, each member of the vector should be smaller than one. Reformulating this vector as an inequality constraint yields:

$$\mathbf{g}_5(\mathbf{t}) = \mathbf{d} - \mathbf{1} \le 0 \tag{14}$$

# 3.4. Optimization algorithms

To have a faster and more robust convergence in the optimization procedure, two different optimization algorithms are successively used. These are the interior point and sequential quadratic programming (SQP) [29]. First, the interior-point algorithm is used to make an unfeasible design a feasible design. Then, the SQP algorithm is used to find the optimum design. The results of the first algorithm serve as the initial value for the second algorithm. Central finite-difference (FD) method is used to calculate the objective function and design constraints gradients vector.

# 4. Results

This section presents the results of the integrated methodology and compares it with the SWT-3.6-107 design. First the optimized design variables are presented, followed by the design constraints. Finally, the optimized objective function is given and compared with the initial design.

# 4.1. Design variables

Figure 3a shows the original and optimized wall thickness of the support structure. As the figure shows, the highest mass reduction is achieved in the transition piece section. The thickness of the tower increases from the tower bottom to the top except the very near end of the tower top where some thickness reduction is achieved. Also, the embedded length of the monopile shows on average an increase in the thickness, but at the mudline a considerable thickness reduction is obtained.

Figure 3b shows the variation of the support structure mass for every single optimization iteration . At the beginning of the optimization process, the scattered behavior is the result of using interior point algorithm to find a feasible design. After finding a feasible design, the SQP algorithm is used, which uses the design variables obtained by interior point algorithm. SQP has a good convergence behavior if provided with a good initial feasible design.

# 4.2. Design constraints

Figure 4 shows the changes in the design constraints. It is noticeable that the buckling constraints are not active design constraints. In this case, the design is driven by the fatigue damage and the first natural frequency as the two active constraints. Because of data confidentiality issues, the initial design constraints are not presented, but it should me noted that also for the initial design the fatigue damage and first natural frequency are the highest active constraints that drive the design.



Figure 3: Figure 3a shows the achieved thickness reduction for the optimized design compared to the initial design, and Figure 3b shows the convergence behavior of the objective function using different optimization algorithms per optimization iteration.



Figure 4: Constraints change during the optimization procedure

## 4.3. Objective function

Table 1 shows the mass reduction percentage of the optimized design compared to the initial design. A mass reduction of 36% is achieved for the optimized transition piece. Also the optimized monopile shows a mass reduction of 11.1%. In contrast, a mass increase of 14.6% is resulted for the tower. In total the integrated mass of the support structure shows 12.1% of mass reduction.

It should be noted that further mass reduction is achievable if the first natural frequency constraints would be relaxed. In this case, fatigue damage would probably remain an active design constraint, but with a different thickness and mass distribution for the support structure to keep it satisfy.

Table 1: Reduced mass in percentage of the optimized design compared to the initial design

	Mass changes [%]
Tower	14.55
Transition piece	-36.0
Monopile	-11.1
Support structure	-12.12

# 5. Conclusion and future work

The goal of this research was to use the integrated design methodology to simultaneously design the monopile, transition piece and tower of an existing offshore support structure. This approach resulted in 12% mass reduction compared to a real design where the monopile, transition piece and tower were design separately by independent parties. This mass reduction shows that having a lighter support structure is possible if all disciplines and components are designed at once. It is therefore recommended to also include the controller design as another discipline [30], and the rotor design as another component to this multidisciplinary design optimization framework. Also, including diameter and length of the sections as design variables is recommended to enable further mass reduction.

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