EOL-OS, SOFTWARE DEDICATED TO THE OPTIMIZATION OF THE SUPPORT STRUCTURE OF OFFSHORE WIND TURBINES

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Abstract: Steel is currently the most common material used in the construction of offshore wind turbines. With towers reaching new heights of over 100 m, and with production, assembly and transportations constraints being more and more heavier, it became obvious that for an offshore wind turbine to become cost effective, the total amount of steel used needed to be minimal. The main objective of EOL-OS is to provide a competitive analysis tool and to perform structural optimizations of the tower of a fixed offshore and onshore wind turbine, in order to obtain either the least cost or the least weight. Thru the use of EOL-OS a wind turbine designer or steel manufacturer can determine what is the best solution in terms of cost or weight, in order yield the maximum benefit from a wind turbine.

Keywords: offshore, optimization, steel, wind turbine

I. INTRODUCTION

Since the very beginning of the century, the wind energy market has started to move offshore because ocean locations offer a higher wind quality and the visual impact of wind farms is significantly reduced. Offshore wind power is now expected to represent an important share of the future power supply both in Europe and worldwide, reducing dependency of industrial countries toward fossil fuels.

The main driver behind the methodology exposed in this paper is the improvement of classical steel solutions dedicated to monopile structures used in off-shore wind industry (Fig. 1). A structural optimization tool has thus been implemented to investigate the gains in terms of weight and production costs generated by the use of high tensile steel for shells, as well as longitudinal and circumferential stiffeners.

Figure 1 Steel monopile offshore wind turbines.

II. GENERAL SCHEME OF THE OPTIMIZATION TOOL

The flowchart of the optimization tool described in this paper is presented in Figure 2. The input data implemented by the designer of the project are at the starting point of the computation. They are related to the environment at the offshore location, the characteristics of the wind turbine and the scantling of the support structure.

The set of selected design variables and input data are then used as a basis to assess the objective function (weight or production cost) and the constraints (structural integrity) of the monopile structure.

A genetic algorithm finally combines these two factors over a certain number of iterations in order to find the optimum scantling of the support structure placed in the given external conditions.

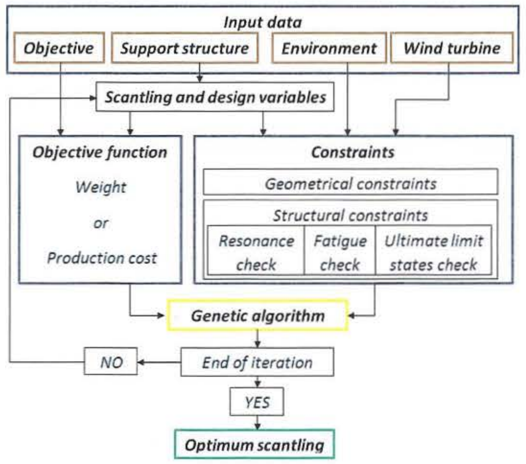


Figure 2 General scheme of the optimization algorithm.

III. INPUT DATA

3.1 Environment

Environmental data summarizes the characteristics of the site, data related to fatigue analysis and load cases considered for the ultimate limit state analysis.

Firstly, site data contains the values for water depth d, the power law exponent α characterizing the vertical distribution of wind speeds over the tower height, the densities of the air ρ_a and of the sea water ρ_w.

Secondly, for fatigue concern a distinction is made between waves and wind actions. On one hand, waves participation is presented under the form of a list of sea states (or scatter diagram), each one being characterized by a significant wave height H_S, a mean zero up-crossing period T_Z and a percentage of occurrence of the sea state P_{SS}. On the other hand, spectrums of punctual tower top loads are used to describe fluctuating wind loadings on the structure.

Finally, data related to ultimate limit states are listed under the form of a series of environmental situations and their associated wind and waves conditions: average wind speed at hub height V_{hub}, water level elevation Δd compared to the mean still water level MSL (elevation due to tide or storm for example), wave height H_w and period T_w and a set of punctual tower top loads.

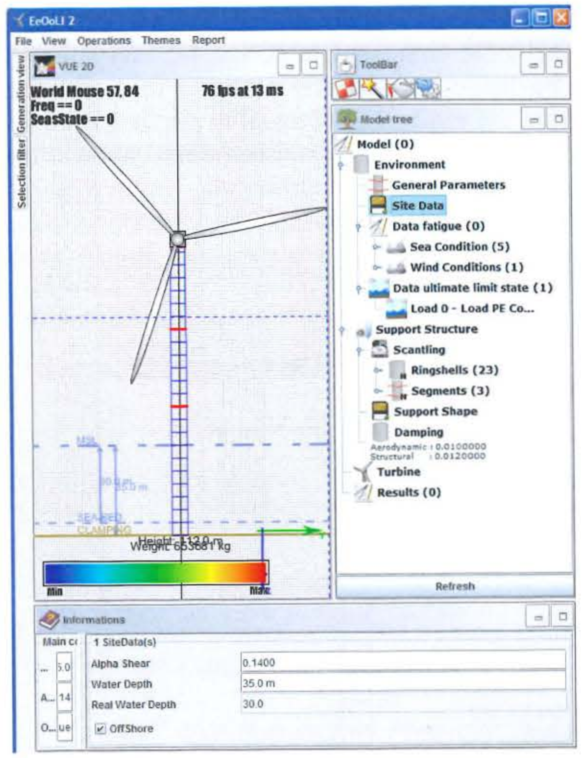
3.2 Support structure

The monopile offshore wind tower considered in the study is an assembly of several conical and cylindrical tubular segments. The segments themselves are made of shell rings linked together with butt welds.

Four framing systems are envisaged for the scantling of shells belonging to the same tower segment: unstiffened, longitudinally stiffened, ring stiffened or orthogonally stiffened shells.

3.3 Wind turbine

Some general data of the wind turbine are taken into account for this preliminary design of the monopile structure: the hub height H_{hub}, the number of blades n, the rotor diameter d_{rotor}, the weight of the rotor-nacelle assembly m_{Top}, the technical design lifetime of the turbine and its range of rotational speed. The interface of the optimization tool is presented in Figure 3.



1 SiteData(s)
Alpha Shear 0.1400
Water Depth 35.0 m
Real Water Depth 30.0
☑ OffShore

Figure 3 Screen shot of the optimization tool.

IV. ASSESSEMENT OF CONSTRAINTS

4.1 Generals

The constraints implemented in the optimization process are typically divided in two categories: geometrical and structural constraints.

The first type of constraints refers to geometrical requirements such as equality of shell rings diameters in one segment or decrease of shell thicknesses and diameters while progressing to the top of the monopile structure.

The second type represents structural constraints related to the verification of the structural integrity of the offshore wind turbine towards fatigue, ultimate limit states and resonance phenomena. The verification of those constraints requires the use of either quasi-static or dynamic analysis of the structure.

4.2 Building the 2D dynamic model

In order to perform dynamic analyses, a simple 2D dynamic model made of concentrated masses connected together with a translational spring is built on the base of the scantling

(Figure 4). Nodes are located at the intersection between shell rings and are characterized by two degrees of freedom: one horizontal translation x_i and one in-plane rotation θ_i (vertical translations are not taken into account as they are supposed negligible compared to horizontal translations). The model is perfectly clamped at a distance from the sea bed level equal to the height of the first shell ring. This assumption allows the designer to take into account the length required for the complete soil restraint to develop around the monopile.

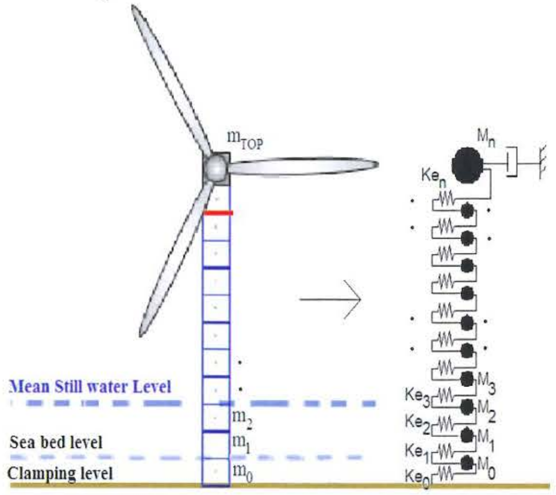


Figure 4 2D dynamic model of the offshore wind turbine studied in the optimization process.

The aerodynamic damping generated by the rotor is modeled with a single dashpot connected to the tower top degree of freedom in translation and the structural damping is expressed thru the Rayleigh damping.

4.3 *Resonance of the support structure*

Excitations are likely to occur at frequencies that are close to the natural frequencies of the offshore wind turbine, leading to resonance phenomena. Natural frequencies and corresponding modes of the support structure are defined respectively from the generalized eigen values λ and eigen vectors of the matrixes of masses [M] and rigidity [K]. The Campbell diagram related to the excitation frequencies for the rotor motion (1n) and the blades passing (3n for a 3-bladed wind turbine) can then be used to check if resonance of the support structure is avoided within the rotational speed range of the wind turbine (Figure 5).

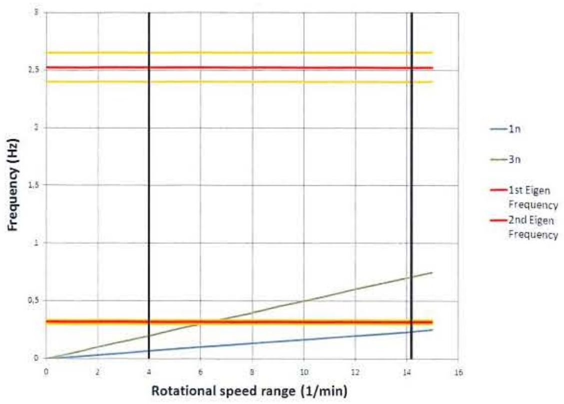


Figure 5 Campbell diagram for a 3-bladed offshore wind turbine.

4.4 *Fatigue check*

Fatigue strength is verified at each structural detail of the support structures (butt welds, ring-stiffener connections, etc.) thanks to the Miner rule (check that cumulative fatigue damage $D_{fat} < 1$).

In addition, the procedure developed for fatigue analysis assumes that wind and waves effects are completely uncoupled. Hence, the total cumulative fatigue damage D_{fat} results from the addition of the fatigue damages due to wind actions $D_{fat,wind}$ and waves actions $D_{fat,wave}$.

Concerning the characteristics of the wind tower, structural members are supposed to be continuous and steel is considered as an isotropic and homogeneous material.

4.5 *Fatigue due to waves actions*

Over its life, the offshore wind turbine will experience a series of sea states, each one generating cyclic loadings and being responsible for a certain percentage of the total cumulative fatigue damage due to waves $D_{fat,wave}$ in the structural components. Thus, for each sea state listed in the scatter diagram, the equations governing the dynamic of the structure and the stress range histogram at the nodes are solved using stochastic dynamic theory in the frequency domain.

At the end, the normal stress range histograms associated to each sea state are summed and conventional S-N curves based on the detail category are used to assess the cumulative fatigue damage due to waves $D_{Fat,wave}$.

4.6 *Fatigue due to wind actions*

For the preliminary design procedure developed in this study, wind loads coming from the rotor-nacelle assembly are completely uncoupled from the dynamic of the support structure. Physically, this approach means that the "transfer" between the 3D wind speeds field and the tower top loads is performed considering that the turbine is connected to an infinitely rigid support. As a result, the value of the cumulative fatigue damage due to wind $D_{Fat,wind}$ is only based on the variations of tower top loads and their associated number of cycles n_{wi}.

4.7 *Fatigue correlation factor*

Because the computation of the fatigue damage due to the waves took about 95% of the optimization time, the need for a simplified way to calculate the fatigue damage arouse.

The solution was found to be a correlation factor between the fatigue damage due to wave and the fatigue damage due to wind. The correlation factor (c) is the ratio between the fatigue damage due to wave, and the fatigue damage due to wind.

At each optimization step, the correlation factor between the two fatigue damages is determined for every ring shell, and then this factor is applied for the remaining steps. This allows for a significant reduction in the optimization time.

4.8 *Ultimate limit states*

The ultimate limit state analysis implemented in this early optimization design stage considers six distributions of internal loads which are:

- F_x: shear force in x-direction;
- F_y: shear force in y-direction;
- F_z: vertical force;
- M_y: bending moment in Oxz-plane;
- M_x: bending moment in Oyz-plane;
- M_z: torque in z-direction.

For each load case considered in the design procedure, those distributions of internal loads result from the superposition of the three following actions:

1. Action of wind on the rotor and nacelle;
2. Action of wind pressure over the height of the emerged tubular structure;
3. Action of waves on the substructure.

The 3D configuration of these three actions is presented on Figure 6.

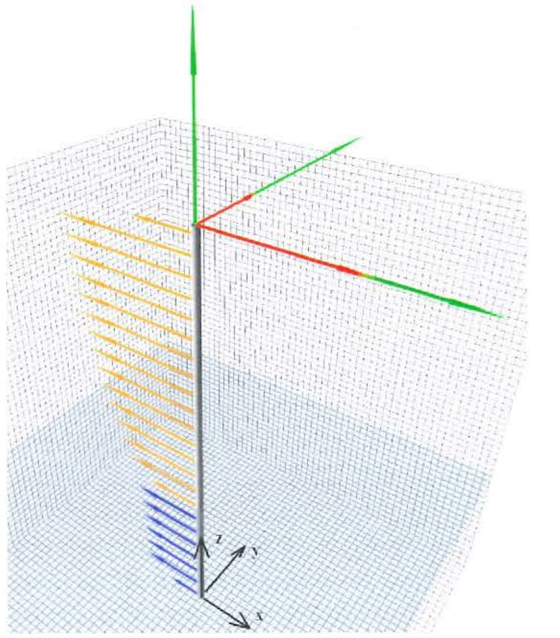


Figure 6 Distribution of wind and waves actions considered for the ultimate limit state analysis.

The distributions of internal loads obtained for each load case are finally combined to find the envelop diagrams of the support structure.

The strength of each shell ring submitted to the design loads defined in the previous paragraph is checked according to the specifications given in DNV [4] or Germanischer Lloyd rules [3]. The following failures modes are considered:

- Shell buckling of unstiffened shell rings;
- Panel stiffener buckling of longitudinally stiffened shell rings;
- Panel ring buckling of transversally stiffened shell rings;
- Overall buckling of orthogonally stiffened shell rings.

An additional constraint is also implemented for the overall buckling of the column.

V. DESCRIPTION OF THE OPTIMIZATION PROCESS

6.1 *Design variables*

The design variables selected for the optimization process are divided in two categories:

- Shell ring variables: shell thickness, lower and upper diameters of the ring, steel grade;
- Segment variables: number and profile of longitudinal and ring stiffeners distributed respectively over the circumference and the height of the segment.

The height of shell rings and segments are not supposed to change during the optimization as they are considered as geometrical data fixed by the de-signer and the manufacturer of the structure.

6.2 Description of the optimizer algorithm

The algorithm chosen for the problem presented in this paper is a genetic algorithm (GA). Genetic algorithms are search algorithms that work via the process of natural selection. They begin with a sample set of potential solutions which evolves towards a set of more optimal solutions after several iterations. Within the sample set, poor solutions tend to die out while better solutions mate and propagate their advantageous traits, introducing better solutions into the set (though the total set size remains constant). A little random mutation guarantees that a set won't stagnate while filling up with numerous copies of the same solution.

6.3 Evaluation of potential solutions

The "fitness function" is responsible for performing the evaluation of solutions compared to each other. Basically, this module returns a positive integer number, or "fitness value", that reflects how optimal the solution is: the higher the number, the better the solution.

The fitness values are then used in a process of natural selection to choose the potential solutions that will survive in the next generation and those that will die out. However it should be noted that natural selection process does not merely select the top x number of solutions. Instead, solutions are chosen statistically so that it is more likely for a solution with a higher fitness value to be selected, but it is not guaranteed. This tends to correspond to the natural world.

VI. OPTIMIZATION OF A 5MW OFFSHORE WIND TURBINE

6.4 Generals

The computerized tool has been tested on the scant-ling of a 5MW offshore wind turbine. The initial monopile support structure considered in the study is made of steel S235.

6.5 Optimization constraints

Concerning the dynamic of the structure, the logarithmic decrements on the first mode due to structural and aerodynamical damping were assumed equal to 0.012 and 0.01 respectively.

The scatter diagram taken into account to assess wave induced fatigue is made of 15 typical sea states observed in the North Sea [1].

Fluctuating wind loads were calculated by an external bureau of study for the wind turbine placed in a dynamic pressure zone IEC IA.

Time domain simulations were performed by the bureau of study with the software NREL Aerodyn to establish the set of extreme tower top loads due to the wind action coupled with the rotor dynamics.

The optimization carried out was based on the minimization of the structural weight of the offshore wind structure.

As the methodology aims to highlight the advantages of using high tensile steel in offshore structures, this optimization was performed on an unstiffened structure made of conventional steel grade S355.

6.6 Optimization results

The evolution of the structural weight and production cost during the optimization process for the unstiffened structure made of steel S355 is presented on Figure 7. It can be seen that the convergence to the optimum solution is ensured after about 1000 iterations.

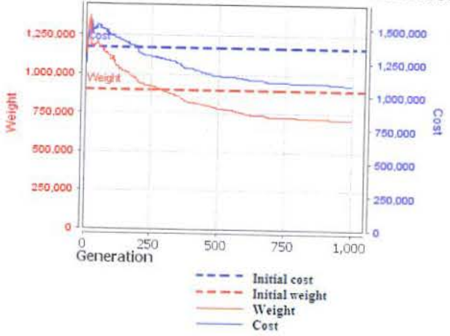


Figure 7 Evolution of weight and production cost during the optimization process

In this optimum scantling, the values of shell rings diameters are slightly lower than in the initial scantling but only for the lower part of the structure (see Figure 8)

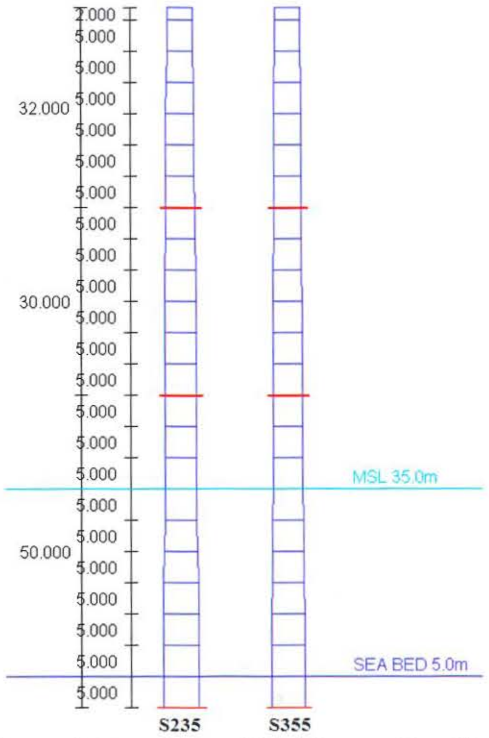


Figure 8 Drawings of initial scantling S235 and optimal scantlings S355

On the other hand, the shell thicknesses are significantly lower in the optimal solution S355. This leads to weight and cost reductions equal to 21% and 20.4% respectively compared to the initial scantling made of steel S235.

VII. CONCLUSION

In this paper, an optimization tool dedicated to the early design stage of steel monopile offshore wind turbines has been described. Constraints related to the structural integrity of the support structure are assessed and an optimum solution in terms of weight or production cost is obtained thanks to a genetic algorithm.

The dimensions of the support structure are reduced while using high tensile steel instead of normal steel grade. As an example, the optimization tool showed that the saves in terms of weight and production cost can reach about 20% when steel grade S235 is replaced by steel S355.

Finally, a certain number of elements could be added to the methodology in future developments. First, the optimization process could be extended to the scantling of the underground part of the support structure.

Second, if the coupling between fluctuating wind loading and structure dynamic is considered at each step of the iteration process, the accuracy of the cumulative damage found from the fatigue analysis would be improved.

Also, a newer and more accurate cost model could be implemented, in order to increase the accuracy of the software.

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