Optimizing an offshore wind turbine monopile for hurricane-prone regions

by Matteo Bucchini[1], Gabriele Degrassi[2]
1. Blom Maritime - 2. ESTECO

The offshore wind energy sector is developing rapidly in the United States. Several new wind farms that use turbines supported on fixed foundations are at various stages of development, especially off the northeast coast. Indeed, there are no plans for floating installations primarily because the continental shelf extends a considerable distance from the shore and so the waters are relatively shallow.

One of the key technical aspects to consider when designing monopile foundations for offshore wind turbines in the US is the occurrence of tropical cyclones along its east coast. The maximum wind speeds of hurricanes can exceed the design limits of wind turbines, making them vulnerable to blade loss, while the supporting monopile foundations can also deform. To tackle this challenge, the goal is to design a wind turbine monopile system that functions even when it is subjected to a critical load such as a strong storm.

Traditionally, the process of developing a design to meet these criteria is iterative and relies on the engineers' skill and project experience. However, modern simulation and numerical analysis techniques were developed to assist engineers to optimize designs according to their set of criteria in less time, which is why we used ESTECO's modeFRONTIER process automation and design optimization software to demonstrate how the design of a monopile for a 15MW turbine can be optimized to survive hurricane conditions.

Investigating the monopile's structural design and response under different environmental conditions

As with any large-scale investment in a project such as an offshore wind turbine farm, numerous factors need to be considered:

- Environment (wind and marine conditions, seabed movement and scour, and conditions such as air temperature, solar radiation, seismicity, maritime traffic, and so on)
- Structure (rotor-nacelle assembly, support structure, energy production and transfer, operation, maintenance, and emergencies)
- Actions/loads (gravitation/inertia, aerodynamics, hydrodynamics, actuation, wake loads, impact loads, tsunamis)

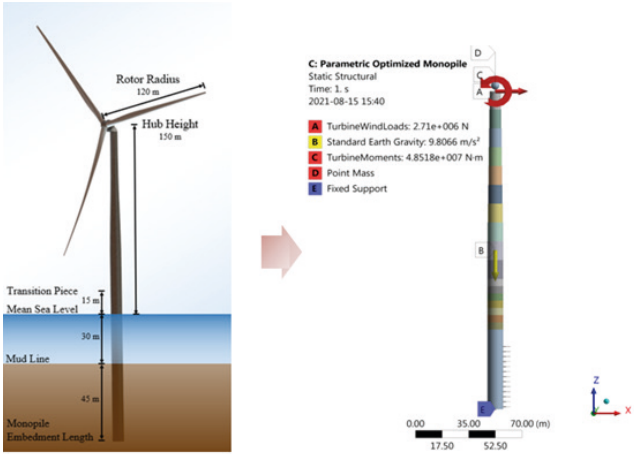

Fig. 1. Structural design of a single wind turbine on a monopile foundation.

The scope of this project is limited to the structural design of a single wind turbine on a monopile foundation. For this study, we used the NREL IEA 15-megawatt offshore reference wind turbine as a starting point. This monopile, which is circular in cross-sections, is 10m in diameter and about 75m long; the thickest segment is the wall thickness, which exceeds 55mm. Based on these considerations we transformed the monopile design into a finite element (FE) model using Ansys Workbench.

Five connected Ansys Workbench blocks form the core of the analysis:

- Three static, structural-analysis blocks cover loads, boundary conditions, and deformation-stress results. Each block covers one load case.
- A modal-analysis block, which is connected to the solution step of the previous block and covers the extrapolation of the natural frequencies from the constrained geometry.
- Additionally, an Excel block is used to incorporate the characteristics of the sandy floor that vary with the depth of the monopile. This block is linked to the parameter set and provides information to the nonlinear springs that are used to represent the soil behaviour.

With regard to the design loads, the monopile foundation is subject to the forces of the waves, ocean currents, winds, and more. Structurally, the wind turbine is designed to cut out at a specific wind speed. In hurricane conditions, the blades are feathered to stop turbine rotation and reduce the loads. Wind loads are calculated for the following conditions using NREL's OpenFAST software:

- Wind speed from max thrust: 11m/s
- Max operational wind speed: 25m/s
- Hurricane conditions: 50m/s

Design optimization process for an NREL 15-MW offshore wind turbine monopile

The optimization-driven process was created and automated in a modeFRONTIER workflow by integrating the Ansys FEA (finite element analysis) model and the NREL OpenFAST software to extract the loads from the operating conditions. The overall aim was to minimize the offshore wind turbine monopile's mass because this parameter is one of the most important influences on the cost, affecting the quantity of material used and the fabrication cost.

Focusing on the overall structural geometry, the primary input design variables considered are the diameters of the base of the monopile and the top of the tower; and the discrete distribution of wall thickness along the height. The main output variables considered are the mass of the monopile, transition piece and tower; the maximum stress experienced; and the natural frequencies of the structure. The design constraints in this problem include the maximum stress experienced by the monopile, buckling checks, and the natural frequencies.

Once the simulation process workflow had been set up, we performed design of experiments (DoE) studies using the uniform Latin hypercube (ULH) algorithm in the modeFRONTIER Planner environment to create 42 configurations of the monopile.

The aim was to minimize the correlations between the input variables and maximize the distance between generated designs

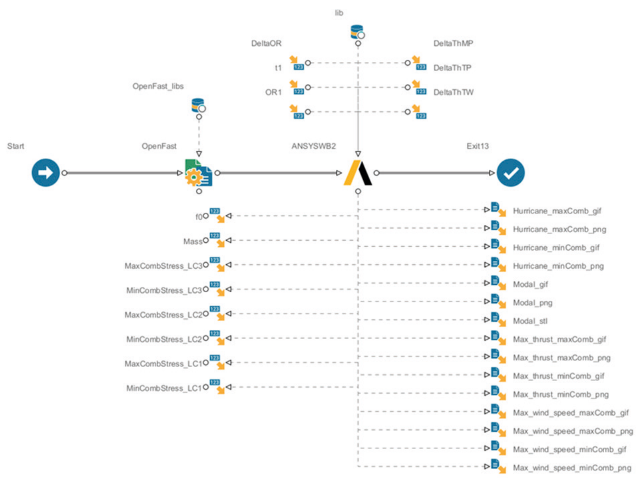

Fig. 2. Automated workflow in modeFRONTIER to minimize the mass of the offshore wind turbine monopile.

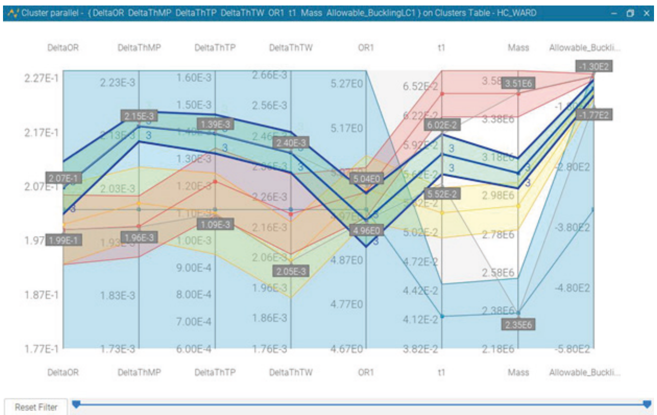

Fig. 3. modeFRONTIER cluster parallel coordinates chart: best cluster selected for virtual optimization.

to explore which areas presented feasible designs before starting the optimization process.

A sensitivity analysis was performed on the results of the DoE, which highlighted the important influence of the t1 (thickness of the first section) and OR1 (outer radius of the first section) parameters on all the outputs. We then applied the FAST RSM-based algorithm to run the design optimization study in modeFRONTIER. This allowed us to concurrently evaluate 202 designs, finding the best feasible design after 150 evaluations.

Starting from the optimization results, modeFRONTIER's clustering tool was used to find the best cluster and this subset was used as the starting point for a virtual optimization on a reduced design space.

The process led to three different designs with apparently better mass values, but validation revealed that they were not, in fact, better than the original best point.

Post-process offshore wind turbine monopile model results in an SPDM framework for collaborative design optimization

To enable us to improve collaboration between the different subject-matter experts involved in this project, the simulation results were uploaded to ESTECO VOLTA – an enterprise platform for simulation process and data management (SPDM) and design optimization.

Thanks to VOLTA Advisor, the advanced web-based data analysis environment, we could collaborate to compare and evaluate the different design results in real time from an interactive dashboard.

In summary, the reduction in mass for the multi-case scenario is lower than for the hurricane condition itself. The result is still significant. By including more loading conditions and design criteria, the result is an increase in the optimized mass value. The weight of the structure has been reduced by more than three percent,

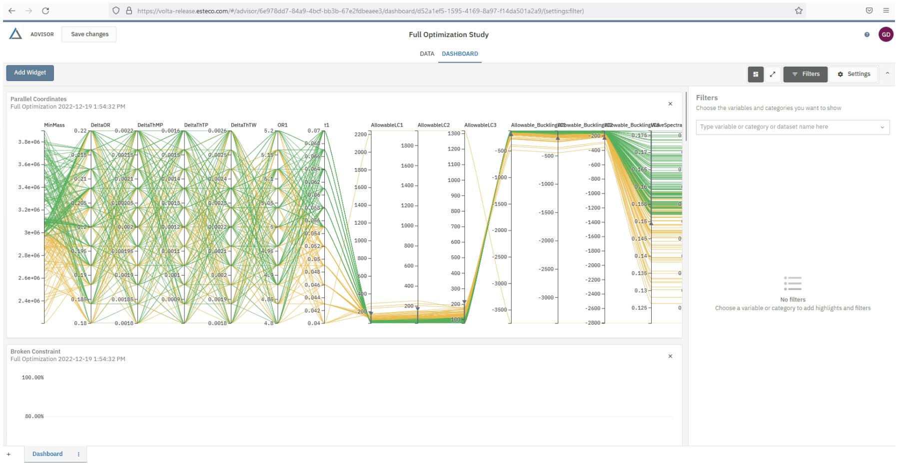

Fig. 4. VOLTA Advisor enables different subject matter experts to collaboratively decide on the best design solution for the NREL 15-MW offshore wind turbine monopile

Name	Initial value	Best Design just LC3	Best Design Common Optimum
Mass [kg]	2.01E+06	1.64E+06	2.01E+06
Δmass%	0.0%	-18.5%	-3.4%

Table 1. Reduction in mass for the multi-case scenario and for the hurricane condition.

however, with an associated reduction in the cost of construction.

The simulation workflow in the VOLTA SPDM platform is impressively powerful: we ran hundreds of designs in half a day, finding the best ones. The VOLTA working environment also provides all the design exploration tools in the same place, which is available via browser from any computer. This is both flexible and powerful.

This research project was undertaken by the HS-03 SNAME panel consisting of the following members and supporting companies: Matteo Bucchini (BLOM Martine); Zhiyong Yang (7C Engineering); Roger I. Basu (Roger Basu & Associates); Aimin Wang (EXMAR Offshore); Won Ho Lee (Lloyd's Register); Gail Baxter (consultant); Robert Sielski (consultant); Raffaele Frontera (HMC); and Gabriele Degrassi (ESTECO).

For more information:
info@esteco.com

The University of New Orleans (UNO), the Louisiana Wind Energy Hub, and DNV held a technical workshop entitled "Expanding Engineering Knowledge for Floating Offshore Wind" at the UNO on April 12, 2023. At the event industry experts from DNV, Principle Power, UNO, Gulf Wind Technology, TAI Engineers, CONVERGE CFD, EXMAR Offshore, and 7C Engineering shared their knowledge about the various aspects of offshore wind ranging from design and manufacturing to supply chain and economics.

The HS-03 panel of the Society of Naval Architect and Marine Engineers (SNAME) reviewed its recent research activities including the forthcoming publication of "Guidelines for Structural Finite Element Analysis of Marine Structures", and the SNAME research paper "Optimum Design of Large Wind Turbine Monopile".

It also announced a new Joint Industry Project (JIP) proposal on Structural Sizing and Load Selection for Early-Stage Design.