Rapid approach for structural design of the tower and monopile for a series of 25 MW offshore turbines

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Abstract. The goal of further reducing the Levelized Cost of Energy (LCOE) has driven the investigation of large-scale wind turbines. This work presents a simple, rapid and detailed approach for the structural design of the tower and monopile without a controller, but with frequency and high fidelity structural verification. The approach uses an optimization to reduce the mass of the structures while meeting strength, buckling and geometric constraints by using analytical equations. A verification of frequency constraints is performed with BModes, and ANSYS Mechanical APDL is used for high fidelity verification of stress and buckling. The approach is applied to study the design space of three 25 MW offshore wind turbines with different rotor diameters and cone angles, and to evaluate the nacelle center of mass fore-aft location effect. Results obtained show that the tower and monopile are more susceptible to changes in the rotor thrust than the overturning moment even for designs with high pre-cone angle and large distance of the nacelle center of mass from the tower axis. But it is possible to obtain structurally feasible tower and monopile designs for the three 25 MW turbines studied while not exceeding diameter and wall thickness limits. However, mass penalties can be decreased by 0.8-14%, to further reduce the cost of energy, by increasing the diameter limit which may require manufacturing technology development. The approach applied and studies serve to understand the design space of the tower and monopile for a 25 MW turbine, and provide baseline designs that can be used in the development of a controller and evaluation of a full suite of design load cases.

1. Introduction

The wind energy community continues to investigate how large horizontal-axis wind turbines (HAWTs) can grow in size, especially offshore, with the goal of reducing the levelized cost of energy (LCOE) while meeting the technology and manufacturing limits of turbine development. Some industry examples of large-scale, offshore, upwind, three-bladed and fixed-bottom HAWTs are the GE 12-14 MW Haliade-X [1], Vestas 15 MW [2], Siemens Gamesa 14-15 MW SG 14-222 DD [3, 4] and MingYang 16 MW [5]. These are current prototypes or are scheduled to deliver the first prototype within the next three years [1]. Some examples developed by universities and research entities are: the IEA 15 MW reference wind turbine developed though the International Energy Agency (IEA) Wind Task 37 working group that is also an offshore, three-bladed and upwind that has models for both floating and fixed-bottom configurations [6], and the Segmented

Ultralight Morphing Rotor (SUMR) project with two-bladed downwind turbine designs of 13.2 MW [7], 25 MW [8] and 50 MW [9]. The Segmented Outboard Articulating Rotor (SOAR) project is a continuation of SUMR and is focused on the study of 25 MW HAWTs, offshore and fixed-bottom designs illustrated in Figure 1. The work presented herein is part of this project. Detailed work was performed during the SUMR project to study rotor designs and control designs, but the tower and monopile was not addressed. In the SOAR project, the rotor and control design remain as key elements, but additional attention has been provided to the tower and monopile because these accounts for at least 30% of the offshore turbine cost and it is necessary to understand trade-offs of growing the turbine size to a 25 MW scale. This work presents a simple, rapid and detailed approach for the structural design of the tower and monopile without a controller, but with verification of frequency using BModes, and of stress and buckling with high fidelity ANSYS Mechanical APDL. This approach is applied to the case study of a series of 25 MW horizontal axis wind turbines with fixed monopile. For this turbine, the effect on the tower and monopile design is evaluated for different (1) rotor designs and pre-cone angles, and (2) fore-aft locations of the nacelle center of mass. These studies are performed to understand the design space of the 25 MW tower and monopile, and to determine feasibility of the designs in relation to current manufacturing limits on diameter and wall thickness. The approach allows obtaining tower and monopile designs that account for the specific characteristics of the wind turbine, and that serve as a baseline for the control design with which a full set of design load cases (DLC's) can be analyzed.

Figure 1. Illustration of SOAR25-V2e turbine used in case studies.

2. Methodology

In this work, a simple, rapid and detailed approach to design the tower and monopile while accounting for the specific characteristics of the turbine (geometric and mass properties of the rotor nacelle assembly, tower and monopile, and aerodynamic performance of the rotor) is presented. This approach allows studying the design space of the tower and monopile, and identifying the feasible design space that is defined by stress, buckling, frequency and manufacturing limits. Tower and monopile designs obtained with this process can then be used in the control design and analyze all DLC's.

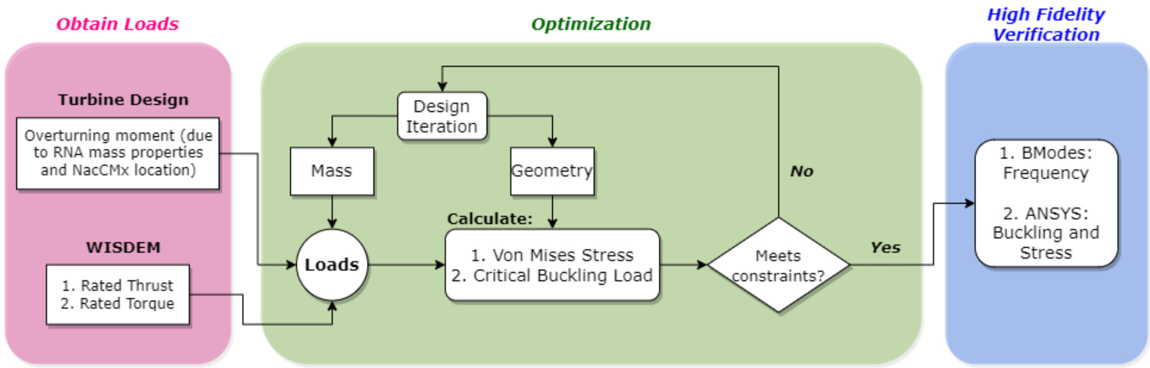


Figure 2. Process for the rapid design of the tower and monopile: (1) Obtain loads, (2) Optimize structure with analytical equations, and (3) Verify frequency (BModes) and structural performance (ANSYS Mechanical APDL).

The process for the rapid design of the tower and monopile is shown in Figure 2. It is assumed that the critical load for steady wind conditions occurs at rated wind speed, but a full set of DLC's would be evaluated later once the control design is complete. First, the Wind-Plant Integrated System Design and Engineering Model (WISDEM) is used to determine the rotor thrust and torque loads. Additionally, the rotor-nacelle-assembly RNA mass properties and overturning moment (moment due to RNA mass) are calculated. Second, the loads are used in an optimization routine that iterates on the geometry (diameter and wall thickness distribution) of the tower and monopile to find a minimal mass solution that meets strength, buckling and geometric constraints. It is important to note that in the optimization process, the mass of the tower and monopile is included in the evaluation of stress and buckling. Finally, feasible solutions are saved and their frequency and structural (strength and buckling) performance are verified using BModes and higher fidelity ANSYS Mechanical APDL, respectively. Further details about the process are provided next.

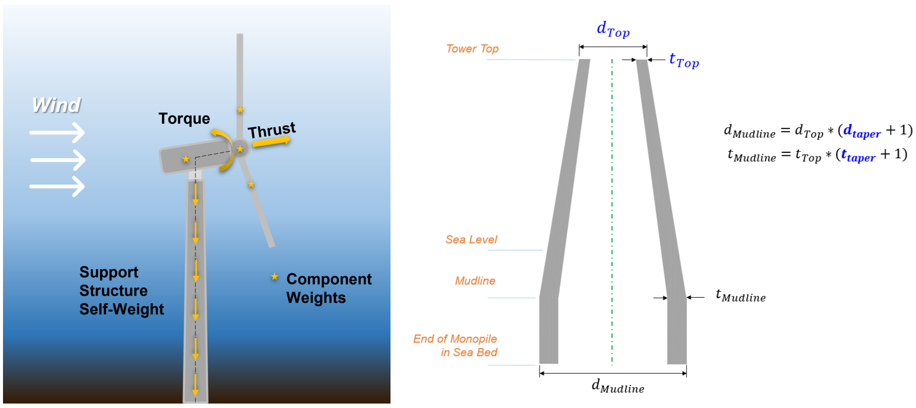
2.1. Optimization Set Up and Assumptions

The optimization shown in Figure 2 is performed with an analytical model, and uses the gradient based and nonlinear programming solver ”fmincon” with the algorithm sequential quadratic programming ”sqp” of MATLAB [10]. This is used because the cost and constraint functions are analytical equations and sufficient constraints are defined. The optimization cost function and constraints are described below:

- Objective: minimize mass of tower and monopile;
- Subject to four geometric constraints illustrated in Figure 3(b), and three structural non-linear inequality constraints evaluated at the mudline (base):
  - (i) 4 m $\leq$ Tower top diameter $\leq$ 9 m;
  - (ii) 0 $\leq$ Diameter taper $\leq$ 1.2 (defines growth of diameter at mudline in reference to diameter at tower top);
  - (iii) 30 mm $\leq$ Tower top wall thickness $\leq$ 100 mm;
  - (iv) 0 $\leq$ Wall Thickness Taper $\leq$ 0.6 (defines growth of wall thickness at mudline in reference to wall thickness at tower top);
  - (v) Fore-Aft (F-A) Von Mises stress $\leq$ 233 MPa (yield strength divided by partial safety factor for metal strength: 350 MPa/1.5);
  - (vi) Side-Side (S-S) Von Mises stress $\leq$ 233 MPa;

(vii) Global buckling factor is ≥ 2.042.

No soil effects are considered at this design stage. Thus, the optimization is performed for the structure between the tower top and the mudline, illustrated in Figure 3(a). The length of the monopile that goes into the sea floor is assumed to have a constant diameter and wall thickness (which are defined to be equal to the designed values at the mudline).



(a) Aerodynamic thrust and torque, tower and monopile self-weight and turbine component weights (blades, hub, nacelle and yaw system)

(b) Cross-section view to indicate the optimization variables (shown in blue): tower top diameter and wall thickness, and diameter and wall thickness taper

Figure 3. Types of loads used in analysis and illustration of variables used in the optimization of the tower and monopile.

The constraints were chosen considering manufacturing constraints and standard material properties described in more detail in the next sub-sections. Based on feedback received, diameters up to 15 m and wall thicknesses up to 100-150 mm are possible to manufacture with current technology. However, thicker walls create challenges in welding and rolling during the manufacturing procedure [11, 12, 13]. Manufacturing limits are considered when evaluating the optimization results.

All loads from Figure 3(a) were used to evaluate strength using the Von Mises stress Equation 1. But only the downward force due to the component weights and the self-weight of the tower and monopile were utilized to evaluate global buckling because the analytical model of column buckling is limited to only use vertical forces. To perform the optimization and analysis, all RNA loads from Figure 3 were transformed to the tower top equivalent forces and moments.

$$\sigma_{vm}(Pa) = \sqrt{\sigma_{bending}^2 + 3 * \tau^2} \quad (1)$$

A partial safety factor of 1.5 was used to evaluate the strength of metal (typical value used for metals that is considered applicable in this work since the analysis is simplified). Additionally, a 1.35 safety factor was included in all aerodynamic loads (environmental loads) and 1.1 for gravity because loads from different origins can be determined independently from each other [14]. Global buckling is evaluated such that the minimum buckling factor (2.042) meets the Germanischer Lloyd (GL) standard for fiber-reinforced shells assuming a linear analysis and a metal material partial safety factor of 1.1 [14].

2.2. Material Properties
The material properties assumed for the optimization and structural analyses correspond to steel and are shown next:

- Young's Modulus = 210 GPa and Poisson's Ratio = 0.3 [15];
- Yield strength = 350 MPa and Ultimate strength = 420 MPa [16];
- Density = 8500 kg/m^3 was assumed to account for the mass of secondary structures such as bolts and flanges. This density was used in the NREL 5MW design [15]. Similarly, the IEA 15 MW design uses 8400 kg/m^3 (steel density of 7850 kg/m^3 plus an additional 7% outfitting mass [6]).

2.3. High Fidelity Frequency, Strength and Buckling Verification
Verification of frequencies, and of stress and buckling are the last step shown in Figure 2. BModes [17] is used to verify that the natural frequencies of the tower and monopile are more than 5% away from 1P and 3P, which is a requirement by Germanischer Lloyd for offshore wind turbines [14]. The analysis in BModes is performed for the structure between the tower top and the mudline, and assuming fully fixed conditions at the mudline for comparative analyses. The frequencies include the effect of adding the corresponding RNA mass and inertia values at the tower top.

ANSYS Mechanical APDL [18] is used to perform high-fidelity verification of the stress and buckling performance of the tower and monopile. For this, static and linear buckling analyses are performed using all loads shown in Figure 3(a) with the appropriate safety factors. The loads included in both static and linear buckling analyses are the following: rotor thrust, rotor torque, RNA overturning moment, RNA weight, and self weight of the tower and monopile (latter one is added by turning on gravity). The model evaluated in ANSYS includes the tower and the monopile section above the mudline. The base of the model is fully constrained and is consistent with the boundary condition used in the optimization. The models for the tower and monopile for the different turbine versions studied are built using AutoNuMAD[19, 20, 21, 9, 7, 22].

3. Case Study: SOAR25-V2 Rotor Design Series
The SOAR25-V2 design series consists of a three-bladed downwind offshore wind turbines with a fixed-bottom monopile that is designed for International Electrotechnical Standard (IEC) Class I-B winds. During the SOAR25 project, the design space of the 25 MW turbine is explored by analyzing different rotor diameters, pre-cone angle, and uptilt among others. In this work, the different rotor configurations and the fore-aft location of the RNA center of mass are used to explore the design space of the tower and monopile for a 25 MW offshore turbine.

3.1. SOAR25-V2 Turbine Designs
Table 1 presents information about three 25 MW turbines that are used in this work to study the the design space of the 25 MW tower and monopile.

The V2c-V2e iterations, shown in Table 1, were obtained by first designing the blade aerodynamics and then the blade structure using WISDEM [23], which has the ability to emulate a extreme gust case for the blade without the need of having a tuned controller. The blade structure was designed to meet strength, deflection and frequency requirements of the industry level engineering design standards including International Electrotechnical Standard (IEC) 61400-1 third edition [24] and Germanischer Lloyd (GL) standard [25]. The design of the tower and monopile is the next step after the rotor design. The resultant blade, tower and

Table 1. General characteristics of SOAR25 V2c, V2d and V2e design iterations

Characteristic	**Units**	**V2c**	**V2d**	**V2e**
Rotor Radius	m	178.75	176	171.75
Blade Pre-cone	deg	18	15	7.5
Shaft Uptilt	deg	0	0	7.5
Rated RPM	rpm	4.871	5.210	5.354
Overhang	m	7		
Hub Height	m	205.793	205.793	199.810
Tower Top Height	m	200.180	200.180	193.287
Tower Length	m	185.180	185.180	178.287
Monopile Length	m	90		
Water Depth	m	30		

monopile design are inputs for the control design with which aero-servo-elastic simulations can be performed.

The rotor design was modified with the objective of minimizing rotor mass and rotor loads while achieving 25 MW. The version V2c has the largest rotor radius and pre-cone angle followed by V2d. Both V2c and V2d do not include uptilt because tower strike is not critical given their large pre-cone values. For V2e, uptilt was added to prevent tower strike and to have a similar blade tip to tower distance as V2d.

3.2. Loads

Table 2 shows the loads for each turbine iteration (V2c-V2e) that are used to design the tower and monopile. These loads correspond to the types shown in Figure 3(a). The weight of the tower and monopile is not tabulated below because it changes for each iteration of the tower and monopile during the optimization. V2d has the largest rotor thrust, followed by V2e and V2c.

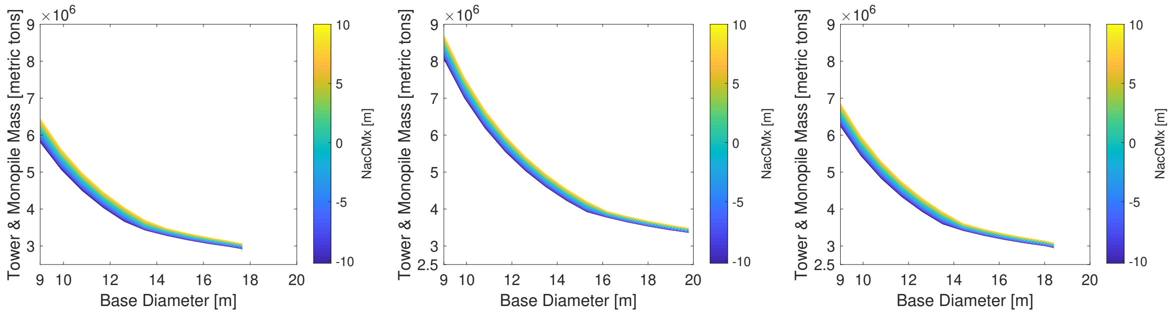
Table 2. Load values used in the optimization and structural analyses

Characteristic	**Units**	**V2c**	**V2d**	**V2e**
WISDEM Rated Thrust [23]	N	4.004E+06	5.678E+06	4.698E+06
WISDEM Rated Torque [23]	N/m	4.901E+07	4.065E+07	4.444E+07
RNA Weight	N	1.715E+07	1.773E+07	1.776E+07

3.3. Results

With the methodology established in Section 2, it is possible to explore the design space of the tower and monopile for the SOAR25 V2c-V2e turbines. Initial assessments of the optimization for a fixed fore-aft location of the nacelle center of mass (NacCMx) show that the active constraints are the structural constraint of Von Mises stress in the downwind fore-aft direction, and the geometric constraints of tower top outer diameter and of diameter taper. The constraint of tower top outer diameter and diameter taper are active because the design is driven by strength (stress), and this is most critical at the base in the downwind fore-aft direction due to the thrust load. Based on this information, in this Section we study the effect of the fore-aft position of the nacelle center of mass (NacCMx) on the design of the tower and monopile for the three turbines.

The position of the nacelle center of mass is not fixed in this project; thus, we are interested in studying the effect of NacCMx on the design of the tower and monopile by using the SOAR25 V2c-V2e turbines. This is also an important consideration given that our focus is on downwind rotors, where the nacelle center of mass is inherently located in a more aft and downwind location. For this, we vary NacCMx from -10.2 m (upwind) to 10 m (downwind), and modify the upper limit of the diameter taper constraint to study tower and monopile desings that vary in maximum/base diameter. Note that relocating the nacelle center of mass upwind can be achieved by moving the generator upwind and using a longer low-speed shaft. However, the impact associated with the long shaft on the generator system's dynamics and structural design needs to be further studied. Additionally, the trade-off between a long shaft and mass savings of the tower and monopile should be considered in future cost analysis. Figure 4 shows the results of varying the NacCMx value (indicated by the colorbar) and the diameter taper limit for the SOAR25 V2c-V2e rotors.



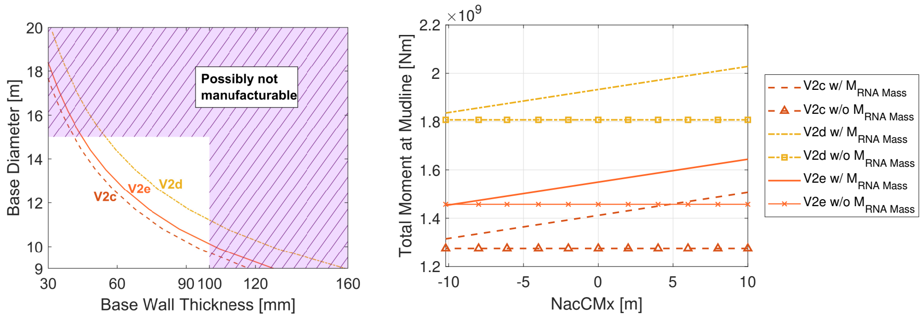
(a) V2c (b) V2d (c) V2e

Figure 4. Mass of the tower and monopile for the SOAR25 V2c-V2e turbines for different NacCMx positions and diameter taper limits.

Figure 4 shows that larger diameter tapers (that equal to larger base diameters and thinner wall thicknesses) result in lower mass tower and monopile designs. The reduction is largest (up to 14%) when comparing "no taper" to "small taper" designs, but only 0.8%-2.5% mass savings are obtained for tapers greater or equal to 0.5-0.7 (approximately equal to 14-16 m base diameters). However, current manufacturing and installation technology may not able to accommodate these large diameters [6], and large wall thicknesses represent a significant challenge in welding and rolling of sections the tower and monopile [11, 12, 13]. Further research may allow determining the limits of current technology as well the need for new factories or equipment to accommodate the requirements of larger wind turbines. Additionally, Figure 4 shows that the mass of the tower and monopile is more sensitive to changes in the outer diameter taper/base diameter than the NacCMx position (which shows a change in tower and monopile mass of 1% per two meter change in NacCMx).

V2c has the smallest tower and monopile mass, base diameters and wall thicknesses as shown in Figure 4 and Figure 5(a). This is followed by V2e and V2d. Figure 5(b) shows that rotor thrust significantly affects the tower and monopile design, even for designs with large pre-cone angle, because it dominates the bending moment at the mudline and the designs were found to be stress critical. The NacCMx value changes the overturning moment load (moment due to RNA mass or $M_{RNA-Mass}$), but the $M_{RNA-Mass}$ is not as significant as the rotor thrust in the tower and monopile design.

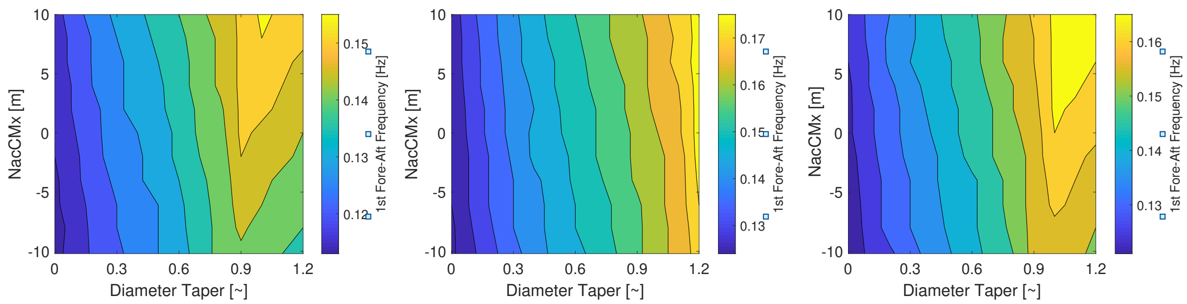
A verification that the designs meet the frequency requirement (described in Sub-Section 2.3) using BModes is shown in Figure 6. This shows the first fore-aft natural frequency of the



(a) Base diameter vs. wall thickness for all positions of NacCMx (b) Total moment at the mudline (base) due to change in NacCMx

Figure 5. Optimization results and comparison of the total moment at the mudline with and without the effect of the RNA mass

tower and monopile for all the turbine versions studied. All frequencies are more than 5% away from 1P (0.081, 0.087 and 0.089 Hz for V2c, V2d and V2e respectively) and 3P (0.244, 0.261 and 0.268 Hz for V2c, V2d and V2e respectively); thus, the designs meet the requirement by Germanischer Lloyd for offshore wind turbines [14]. The first fore-aft frequency is smallest for V2c because this rotor has the lowest thrust that results in the combination of smallest base diameter and wall thickness as shown in Figure 5(a). V2c is followed by V2e and V2d because the thrust value of V2e is higher than V2c but lower than V2d. Additionally, Figure 6 shows that the diameter taper has a larger effect on this mode than the NacCMx location; thus, the contour lines appear steeper.



(a) V2c (b) V2d (c) V2e

Figure 6. 1st fore-aft natural frequency of the tower and monopile structures for the SOAR25 V2c-V2e turbines

The static and linear buckling analyses with ANSYS Mechanical APDL [18] are only performed for V2e due to limitations on computational resources. Figure 7 shows that the structure does not fail for any combination of nacelle center of mass position and diameter taper (all buckling factors are above 2.042) except for small enclosed regions indicated by the white arrows where the buckling factor is lower than the allowable by up to 2%. The results show that the structure is more prone to buckling with higher diameter tapers because these result in larger outer diameters with smaller wall thicknesses. An assessment of the Von Mises stress results indicates that the maximum stress (which occurs on the downwind side) is within an average of 9% from the analytical stress that may be due differences in fidelity of ANSYS compared to the analytical equations used in the optimization. This stress difference is not considered critical at this design stage, but will be taken into account in future work.

4. Conclusions

In this work, a simple, rapid and detailed approach for the design of the tower and monopile structures without a controller, but with frequency and high fidelity structural verification is presented. This method allows obtaining baseline designs (based on the specific characteristics of the turbine) that can later be used in a high-fidelity control design and full DLC analyses. The approach applies an optimization based on analytical equations to the reduce the mass of the tower and monopile while meeting structural and geometric constraints. Then, verification that the resultant designs meet the requirements is performed with BModes for frequency, and with ANSYS Mechanical APDL for stress and buckling.

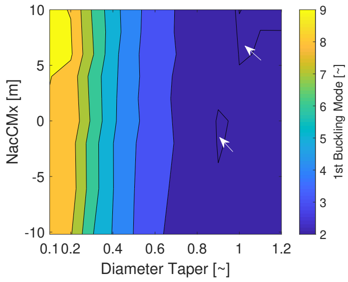


Figure 7. 1st buckling mode for optimized tower and monopile designs corresponding to the SOAR25 V2e turbine.

The approach is used to study the design space of the tower and monopile of a series of offshore 25 MW horizontal axis and fixed-bottom turbines. Analyses are performed considering different rotor configurations (rotor diameter, blade blade pre-cone and shaft uptilt), and various fore-aft locations of the nacelle center of mass (affects the total load applied to the tower and monopile). Results indicate that the tower and monopile design significantly depend on value of the rotor thrust, as turbines with higher thrust result in heavier tower and monopile designs. The effect of the overturning moment in the design of the tower and monopile is observed to be small compared to the thrust, even for designs with high pre-cone angle and large distance of the nacelle center of mass from the tower axis. Additionally, the studies show that it is possible to obtain structurally feasible tower and monopile designs for the series of 25 MW rotor designs studied herein while not exceeding the manufacturing limits on diameter and wall thickness. However, lower mass (reduction 0.8-14%) designs seem possible by allowing larger diameters.

The approach developed and the design studies performed allow the rapid study of the design space of the tower and monopile, and to identify important trade-offs of growing the size of wind turbines to 25 MW even from an early design stage. Future research would focus on studying trade-offs with a tuned controller and full DLC analyses (obtained using selected baseline designs from the results presented herein).

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