Modeling and dynamic analysis of 15 and 22-megawatt offshore wind turbines using PyMAPDL

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Abstract. Offshore wind energy has emerged as a crucial component of renewable energy systems, offering substantial potential for large-scale electricity generation. Effective design and optimization of Offshore Wind Turbines (OWTs) are essential to ensure their performance and durability under various environmental conditions. This paper presents advances in Finite Element Modeling (FEM) tailored for 15-MW and 22-MW OWTs using PyMAPDL. Integrating these models into a Python-based graphical user interface (GUI) enables a comprehensive dynamic response analysis, incorporating hydrodynamic and aerodynamic simulations. Comparative assessments against an existing 5-MW model elucidate key performance metrics related to structural integrity and operational efficiency. The results provide critical insights into the scalability and operational capabilities of larger OWT installations, setting the foundation for future innovations in OWT technology.

Keywords: offshore wind turbine; structural control; finite element modeling; spectral analysis.

1 Introduction

Offshore wind energy has emerged as a pivotal renewable energy source due to its potential for large-scale electricity generation. The design and optimization of Offshore Wind Turbines (OWTs) are critical for enhancing their performance and durability under various environmental conditions. Recent advances in vibration control mechanisms have significantly contributed to mitigating the dynamic response of OWTs, thereby improving their operational efficiency and useful life.

In prior research, the authors have extensively investigated different vibration control strategies using a 5-MW OWT model developed by the National Renewable Energy Laboratory (NREL) [1]. These studies have explored the use of tuned liquid column dampers (TLCD), pendulum-tuned mass dampers (PTMD), and metamaterials for vibration mitigation.

Mendes et al. [2] performed a parametric optimization of TLCDs to mitigate the dynamic response of 5-MW NREL OWTs, considering the interaction of soil-structure interaction. The study used a genetic algorithm to optimize the TLCD parameters, resulting in significant reductions in the root mean square (RMS) displacements at the top of the tower under random wind and wave forces.

Colherinhas et al. [3] presented an optimal design procedure for PTMDs to control the global structural vibrations of OWTs. Their work highlighted the importance of incorporating flexible non-linear monopile foundation modeling and utilized a probabilistic approach within the Performance-Based Wind Engineering (PBWE) framework to assess and analyze structural risks. The efficacy of PTMDs was demonstrated through power spectral density (PSD) analysis, showing substantial vibration reduction in the fore-aft and side-side directions.

Machado et al. [4] introduced a novel approach using mechanical metamaterials for the control of OWT vibration. Their study emphasized the efficiency of metamaterials in creating tunable stopbands and reducing vibration amplitudes under multiple-hazard excitations, offering superior performance compared to conventional tuned mass dampers.

The present study advances the state of the art by developing comprehensive FEM models for 15 and 22 MW OWTs [5, 6] using PyMAPDL [7]. This new model is integrated into a graphical user interface (GUI) developed in Python, which allows users to input relevant wind and maritime conditions. The developed tool utilizes finite element modeling (FEM) via PyMAPDL, extending the functionality of MAPDL (ANSYS) with a Python interface.

This integration enables detailed hydrodynamic and aerodynamic modeling, including rotational spectra of the blades, wind, and wave, facilitating comprehensive dynamic response analysis through Power Spectral Density (PSD).

The paper is structured as follows. Section 2 describes the methodology using the Python algorithm and the global structure of the OWT, including the development and analysis of FEM models for 15-MW and 22-MW OWTs using PyMAPDL. Section 3 presents the results, focusing on the dynamic response of the structure. Section 4 concludes the study with key findings and future research directions.

2 Methodology

2.1 Graphical User Interface (GUI)

The graphical user interface (GUI) is initialized by the `gui_module.py` function (see Figure 1). The GUI presents a selection list with the OWTs: NREL 5-MW, IEA 15-MW and IEA 22-MW. It also includes an area reserved for defining environmental actions, where users can activate wind and wave effects simultaneously, select the type of wind (Kaimal or White noise) and wave (Pierson-Moskowitz or JONSWAP), and input metocean data (US East Coast site, Gulf of Maine, or Hs and Tp as a function of U_{10m}). Another area is reserved for defining structural properties, including a ”Structural control” list (not yet implemented), a ”Foundation type” list (not yet implemented), and a ”Node definition” section for defining tower nodes (along and across), wave nodes, and foundation nodes. Upon selecting an OWT, an image of the selected OWT is displayed on the right side of the GUI [5], and the default values for a standard simulation are loaded. These values can be altered for a customized simulation.

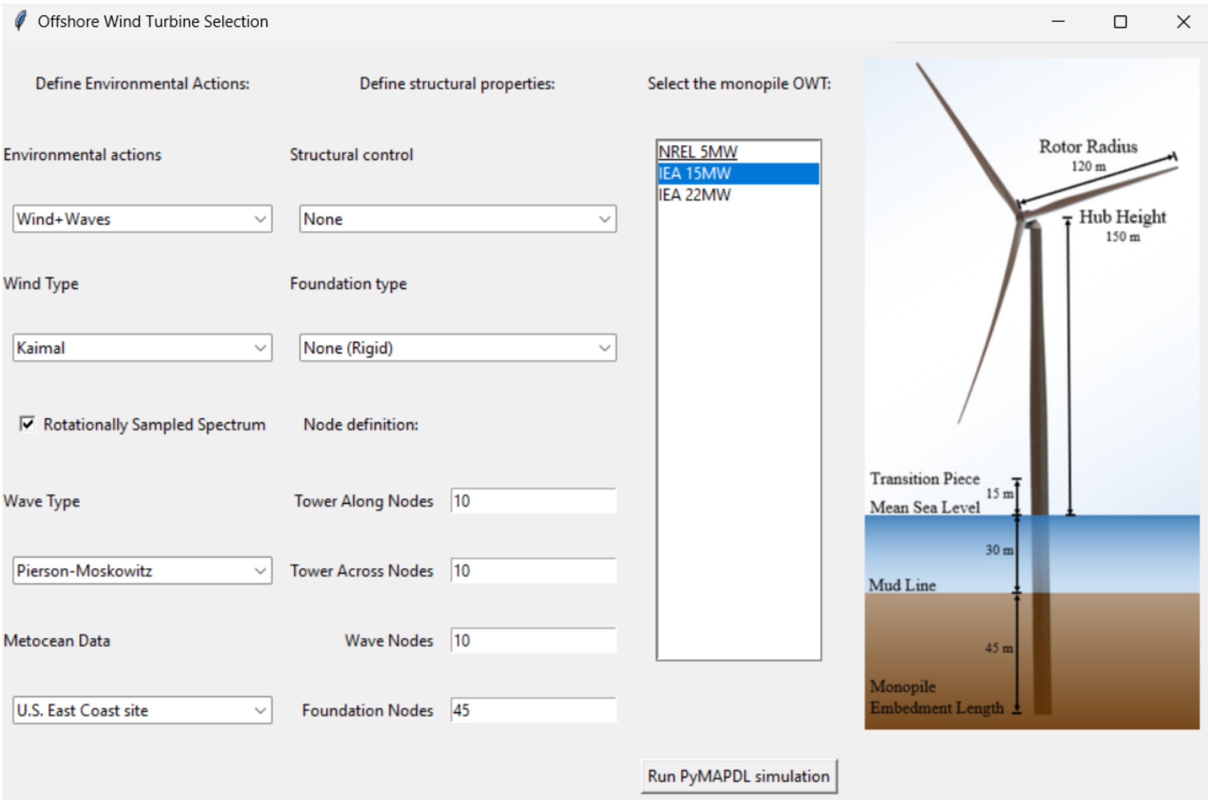

Figure 1. Graphical User Interface (GUI) for selecting and defining simulation parameters for OWTs.

2.2 Python Functions

The program utilizes two batches of functions: `A_Python.py` and `B_PyMAPDL.py`.

`A_Python.py` Functions

The `A_Python.py` functions are responsible for:

- Defining the necessary inputs by reading the selections made in the GUI. These parameters are imported from OpenFAST-defined variables based on the baseline OWTs. A database in Excel spreadsheets contains all information related to the 5-MW, 15-MW and 22-MW towers, including pitch controller data and aerodynamic information related to defined airfoils, which will be used for calculations using the Blade Element Momentum (BEM) theory. The definitions of the tower geometry (see Figure 2), such as the diameters and thicknesses (respectively, D and T) of the monopile (mon), base and top sections, the nacelle and rotor mass (m) and their positions (overhang and shaft tilt), meta-ocean data and rated wind speed are also read from this database.

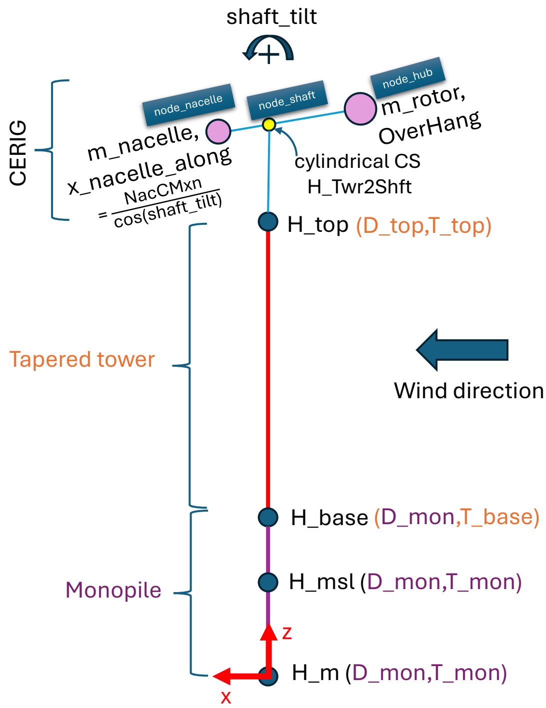

Figure 2. Input data for tower geometry.

- Calculating induction factors using aerodynamic calculations as defined by Burton et al. [8] with BEM, estimating axial thrust and torque, rotor power, and power coefficient, including tip and hub losses, and Glauert correction.
- Defining wind forces, wind spectrum, rotationally sampled spectrum, hydrodynamic loads, wave kinematics, and wave spectrum [1].

`B_PyMAPDL.py` Functions

The `B_PyMAPDL.py` functions use PyMAPDL to:

- Define tower parameters using element types: BEAM188 for the tower, PIPE288 for the monopile, and MASS21 for the mass of the hub and nacelle. Real constants are defined from the inputs for the selected OWT, including material properties and tapered sections.
- Create a line mesh from keypoints defined by the number of nodes and geometric information provided in Figure 2.
- Perform a modal analysis to extract natural modes and frequencies.
- Perform a spectral analysis applying the calculated wind spectra to the tower in along and across directions, along with the wave spectrum and rotationally sampled spectrum.

- Conduct a static analysis to apply wind and wave actions. The static response is used to calculate the dynamic structural response and the standard response deviation σ_r, which relates to the effects of turbulent wind and waves obtained from spectral analysis. In the across-wind direction, at certain critical ranges for mean velocities, the frequency of vortex shedding around the tower coincides with the first natural frequency of the lateral tower motion, resulting in lock-in vibration. Maximum across-wind displacement r_{VS}^{across} is applied to the tower to consider the lock-in effect for a range of reduced velocities U_R [9, 10].

$$r_{VS}^{across} = \frac{1.29D}{1 + 0.43(2\pi ScSt^2)}, \quad \text{for } \frac{0.8}{St} \leq U_R \leq \frac{1.6}{St} \tag{1}$$

where $U_R = U_{hub}/(n_1 D)$, n_1 is the first natural frequency, D is the mean tower diameter, and Sc and St are the Scruton and Strouhal numbers, respectively.

- Calculate the dynamic structural response as described in [3]. The peak dynamic structural response r_p is computed as follows:

$$r_p = r_m + g_r \cdot \sigma_r \tag{2}$$

where r_m is generated by the mean wind (including the vortex being shed on the tower) and sea current from static analysis, and σ_r relates to the effects of turbulent wind and waves obtained from spectral analysis using the response peak factor $g_r = \sqrt{2\ln(v \cdot T_{wind})} + 0.577/\sqrt{2\ln(v \cdot T_{wind})}$, where v is the cycling rate of the structural response (equal to the first eigenfrequency of the system) and T_{wind} is the evaluation time interval (3600 sec in this paper).

- Perform a final static analysis applying the dynamic structural response r_p at the top of the tower, allowing the calculation of the resultant stress at the base.

3 Results

This section presents the results of the dynamic structural response and resultant stress at the base for the 5, 15, and 22-MW OWTs modeled using PyMAPDL. Table 1 presents the first six natural frequencies (in Hz) for the three OWTs in fore-aft (FA) and side-to-side (SS) directions, considering the monopile fixed at sea-bottom.

Table 1. First six bending natural frequencies (Hz) for the 5-MW, 15-MW, and 22-MW OWTs.

Mode	NREL 5-MW	IEA 15-MW	IEA 22-MW
First FA	0.27	0.17	0.15
First SS	0.28	0.18	0.15
Second FA	2.23	1.25	0.97
Second SS	2.30	1.32	1.02
Third FA	5.61	3.07	2.44
Third SS	6.15	3.80	2.93

For all OWTs, Kaimal spectra were used for wind and Pierson-Moskowitz spectra for waves. The rotational effects of the blades were considered using the Rotational Sampled Spectrum, and the foundation was modeled as rigid (fixed at the seabed). The interval for the effects of vortex shedding was included, considering $St = 0.2$, with a range of $4.00 \leq V_R \leq 8.00$ m/s. Table 2 presents the input parameters used for the three OWTs. The variables used in the tables below are:

- V_{hub}: Rated wind speed at the hub
- Hs: Significant wave height
- Tp: Wave period
- V_R: Reduced wind velocity
- r_{along}: Dynamic response in the along-wind direction
- r_{across}: Dynamic response in the across-wind direction
- σ_{base}: Resultant stress at the base
- Lock-in: Whether the lock-in effect was considered

Table 2. Load cases for rated wind speed for the 5-MW, 15-MW, and 22-MW OWTs.

OWT	V_{hub} [m/s]	Hs [m]	Tp [s]	V_R [m/s]	Lock-in
NREL 5-MW	11.4	6.00	10.00	8.38	No
IEA 15-MW	10.8	4.52	9.45	7.45	Yes
IEA 22-MW	11.0	7.60	13.00	8.97	No

Table 3 shows the dynamic structural response (along and across directions) and the resulting stress at the base of the three OWTs. These results were obtained using the PyMAPDL functions described in the methodology.

Table 3. Results of the dynamic structural response and resultant stress at the base for the 5-MW, 15-MW, and 22-MW OWTs.

OWT	r_{along} [m]	r_{across} [m]	σ_{base} [MPa]
NREL 5-MW	1.07	0.87	161.51
IEA 15-MW	2.10	2.06	298.40
IEA 22-MW	2.97	2.27	276.00

The results in Table 3 indicate that the dynamic responses increase with the size of the turbines. The 15 MW IEA OWT exhibited a lock-in effect, which significantly increased its dynamic structural response and the resultant stress at the base compared to the 22 MW IEA OWT, despite the latter being larger.

The dynamic response along the wind direction (r_{along}) and across the wind direction (r_{across}) for the NREL 5-MW was 1.07 m and 0.87 m, respectively, with a resultant stress at the base (σ_{base}) of 161.51 MPa. For the IEA 15-MW, the dynamic responses were 2.10 m (r_{along}) and 2.06 m (r_{across}), resulting in a stress of 298.40 MPa at the base. The IEA 22-MW had the highest dynamic responses, with 2.97 m (r_{along}) and 2.27 m (r_{across}), but a lower resulting stress at the base (σ_{base}) of 276.00 MPa compared to the IEA 15-MW, due to the absence of the lock-in effect.

Figure 3 illustrates the Power Spectral Density (PSD) responses of the NREL 5-MW, IEA 15-MW, and IEA 22-MW models. The left sub-plot shows the along-wind PSD response, while the right sub-plot depicts the across-wind PSD response. PSD values are plotted against the frequency range from 0 to 0.5 Hz, revealing higher PSD values at lower frequencies for the IEA 15 MW and IEA 22 MW models, indicating a more pronounced response to low-frequency excitations. In contrast, the NREL 5-MW model shows a more significant response at higher frequencies in both directions. These results highlight the different dynamic characteristics and responses of the three turbine models, which are critical to understanding their performance under various wind conditions.

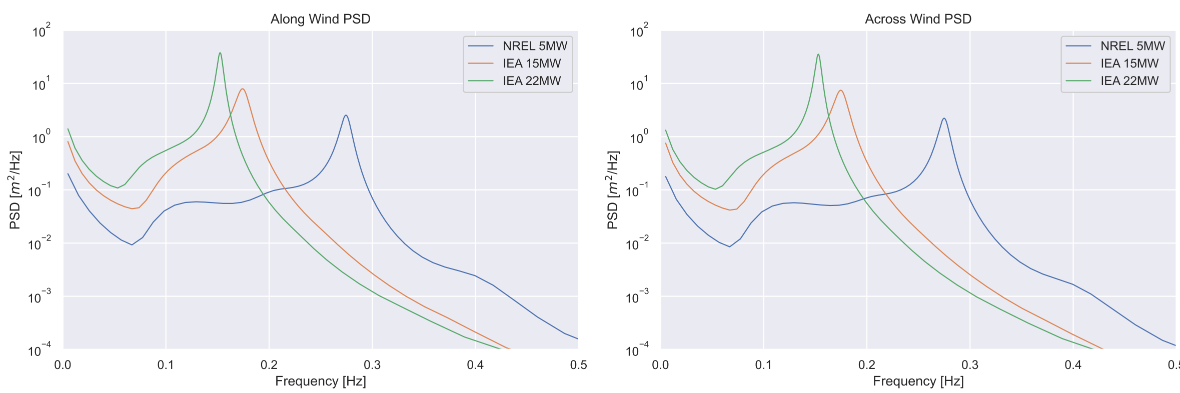

Figure 3. Power Spectral Density (PSD) responses of the NREL 5-MW, IEA 15-MW, and IEA 22-MW models. The left subplot shows the along-wind PSD response, while the right subplot depicts the across-wind PSD response.

The current study utilizes Python and PyMAPDL, providing a more straightforward and efficient solution compared to previous research methods that combined MATLAB with ANSYS APDL. The previous approach required the creation of temporary files to store vectors and matrices in MATLAB, which were then read by

ANSYS APDL in separate instances initialized by MATLAB. The PyMAPDL approach leverages the variables already defined in Python, simplifying the implementation and reducing the complexity of the code.

The results demonstrate the effectiveness of the Python program developed and PyMAPDL functions in analyzing the dynamic structural response of OWTs. The inclusion of the lock-in effect, presented in the IEA 15 MW OWT, significantly impacted its dynamic response and the resultant stress at the base, highlighting the importance of considering such phenomena in OWT design and analysis.

4 Conclusions

This study has made significant strides in the modeling and analysis of OWTs, specifically focusing on the development of 15-MW and 22-MW models using Python and PyMAPDL. Through a comprehensive approach, the research has yielded several key insights and findings.

The comparative analysis of the dynamic structural responses of the 5-MW, 15-MW, and 22-MW OWTs revealed that larger turbines experience significantly higher dynamic responses. This underscores the importance of precise modeling and robust structural design to ensure the stability and efficiency of larger turbines under various environmental conditions. The increased dynamic responses with turbine size highlight the necessity for advanced engineering solutions to mitigate these effects.

One of the pivotal developments in this study was the incorporation of the lock-in effect for a range of reduced velocities in the code. This aerodynamic phenomenon, which can induce significant vibrations when the frequency of vortex shedding matches the natural frequency of the structure, was successfully modeled to evaluate its potential impact on turbine performance and structural integrity. This enhancement allows for a more comprehensive assessment of turbine behavior under specific aerodynamic conditions.

The transition from traditional modeling approaches using MATLAB and ANSYS APDL to a more integrated and efficient workflow with Python and PyMAPDL demonstrated clear advantages. The new methodology streamlined the process, eliminating the need for intermediate data files and facilitating a more seamless integration of computational tools. This advancement not only simplifies the modeling process but also enhances the accuracy and efficiency of simulations, paving the way for more sophisticated analyses in future research.

Despite the significant progress, this study acknowledges that certain aspects, such as flexible foundations and advanced vibration control mechanisms, were not implemented. Future research should focus on incorporating these elements to provide a more holistic understanding of OWT behavior under diverse operational conditions. Additionally, further exploration into optimizing turbine performance and resilience against environmental forces remains a crucial area for ongoing investigation.

In conclusion, this research has contributed valuable knowledge and tools for the advancement of offshore wind energy technology. By leveraging modern computational techniques and detailed FEM analysis, the study provides a solid foundation for future developments in the design, analysis, and optimization of OWTs. The findings underscore the importance of continuous innovation and refinement in renewable energy engineering to meet the growing demands for sustainable and reliable energy solutions.

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References

[1] G. B. Colherinhas, F. Petrini, de M. V. G. Morais, and F. Bontempi. Optimal design of passive-adaptive pendulum tuned mass damper for the global vibration control of offshore wind turbines. *Wind Energy*, vol. 24, n. 6, pp. 573–595, 2021.

[2] M. V. Mendes, G. B. Colherinhas, de M. V. G. Morais, and L. J. Pedroso. Optimum tlcd for mitigation of offshore wind turbine dynamic response considering soil–structure interaction. *International Journal of Structural Stability and Dynamics*, vol. 23, n. 19, pp. 2350187, 2023.

[3] G. B. Colherinhas, de M. V. G. Morais, and F. Petrini. Global vibration control of offshore wind turbines with a flexible monopile foundation using a pendulum-tuned mass damper: Risk mitigation and performance incrementation. *Ocean Engineering*, vol. 297, pp. 117168, 2024.

[4] M. Machado, M. Dutkiewicz, and G. Colherinhas. Metamaterial-based vibration control for offshore wind turbines operating under multiple hazard excitation forces. *Renewable Energy*, vol. 223, pp. 120056, 2024.
[5] E. Gaertner, J. Rinker, L. Sethuraman, F. Zahle, B. Anderson, G. Barter, N. Abbas, F. Meng, P. Bortolotti, W. Skrzypinski, G. Scott, R. Feil, H. Bredmose, K. Dykes, M. Sheilds, C. Allen, and A. Viselli. Definition of the IEA 15-megawatt offshore reference wind turbine. Technical report, Technical University of Denmark, International Energy Agency, 2020.
[6] F. Zahle, A. Barlas, K. Lønbæk, P. Bortolotti, D. Zalkind, L. Wang, C. Labuschagne, L. Sethuraman, and G. Barter. Definition of the IEA Wind 22-Megawatt Offshore Reference Wind Turbine. Technical Report DTU Wind Report E-0243, https://doi.org/10.11581/DTU.00000317, Technical University of Denmark, International Energy Agency, 2024.
[7] A. Kaszynski. pyansys: Pythonic interface to MAPDL. Technical report, Zenodo, 2021.
[8] N. Jenkins, T. Burton, E. Bossanyi, D. Sharpe, and M. Graham. *Wind Energy Handbook 3e*. Wiley, 2021.
[9] C. Borri and S. Pastò. *Lezioni di ingegneria del vento*, volume 1. Firenze university press, 20 edition, 2006.
[10] DNVGL. *Recommended practice: environmental conditions and environmental loads*. DNV-GL-RP-C205 Standard, 2017.