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Klaus Müller
School of Engineering, University of Auckland, New Zealand

Emily Chang
School of Engineering, University of Auckland, New Zealand

Corresponding Author:
Klaus Müller
School of Engineering, University of Auckland, New Zealand

Dynamic analysis of marine structures in offshore wind farms using fluid-solid interaction models

Klaus Müller and Emily Chang

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Abstract
Offshore wind farms (OWFs) have gained significant importance as a renewable energy source, especially in regions with abundant wind resources and available coastal areas. The structural integrity and durability of marine structures within OWFs, including turbines, foundations, and related infrastructure, are critical to their long-term performance and economic feasibility. This paper investigates the dynamic analysis of marine structures in offshore wind farms using fluid-solid interaction (FSI) models. FSI simulations provide a comprehensive approach to researching the interaction between the surrounding fluid (ocean water) and solid structures (wind turbines and foundations). These simulations incorporate the effects of hydrodynamic forces, wave loads, and environmental conditions, which are vital in ensuring the safety and resilience of marine structures. A detailed analysis of these interactions can optimize the design and enhance the operational efficiency of OWFs by reducing the risk of structural failure caused by dynamic forces. The research examines various FSI models, evaluates their accuracy, and assesses their ability to predict the behavior of marine structures under different operating conditions. The objective is to identify the most effective modeling approaches and to explore the impact of FSI on the design and maintenance strategies of offshore wind farms. Through numerical simulations, the paper explores factors such as wave-structure interaction, fluid flow patterns, and vibration frequencies that influence the performance of these structures. The results of this research contribute to a better understanding of the dynamic behavior of OWFs, providing insights for improving the design, maintenance, and operational planning of offshore wind energy systems.

Keywords: Offshore wind farms, fluid-solid interaction, dynamic analysis, marine structures, wave loads, numerical simulations, structural integrity, renewable energy, hydrodynamics, vibration frequencies

Introduction

Offshore wind farms (OWFs) represent a promising solution to meet global energy demands through renewable resources. They provide the opportunity to harness strong wind flows in coastal areas, where wind speeds are consistently high. However, the installation and maintenance of offshore wind turbines face unique challenges due to the dynamic environmental conditions of the marine environment, such as wave motion, tides, and varying sea states. Understanding how marine structures interact with these dynamic forces is essential for optimizing the design and ensuring the longevity of offshore wind turbines and their supporting structures.

The primary issue in the structural analysis of OWFs lies in the interaction between the fluid (water) and solid structures (wind turbines and foundations). The dynamic loads induced by waves, currents, and wind have a direct impact on the structural performance of these systems. Traditional structural analysis methods often fail to capture the complexity of this interaction, which can lead to underestimations in the design parameters and potentially catastrophic failure. To overcome these limitations, fluid-solid interaction (FSI) models are increasingly used to provide more accurate simulations of how offshore wind farm structures behave under real-world environmental conditions [1]. These models account for both the structural deformation and the fluid's influence on the dynamics of the system, offering a holistic approach to design optimization [2].

The objectives of this research are to explore the role of FSI in offshore wind farm structural analysis and to identify the best modeling practices for simulating dynamic interactions between marine structures and the surrounding fluid. This research will investigate different simulation approaches, including the application of computational fluid dynamics (CFD) combined with structural models to examine the effects of wave-structure interactions and their impact on the overall stability of offshore structures. The hypothesis is that accurate FSI models can improve the structural design of offshore wind turbines by accounting for the complex dynamics of the marine environment, thereby enhancing both performance and safety [3].

Materials and Methods

Materials

The materials for this research consist of offshore wind turbine structural components, ocean wave simulation data, and computational fluid dynamics (CFD) software tools for fluid-structure interaction (FSI) modeling. The marine structures include wind turbine towers, floating foundations, and mooring systems, modeled using detailed CAD (Computer-Aided Design) representations. Ocean wave data used in the simulations are derived from long-term wave height and frequency datasets collected from a coastal region with a high offshore wind potential. The simulation tools employed in this research include OpenFOAM for CFD simulations and ANSYS Mechanical for structural analysis. These tools are used to model the dynamic behavior of the marine structures subjected to wave and wind loading. Data sets from previous offshore wind farms were used to validate the FSI models. The wave patterns considered in the research are based on realistic sea states, including storm conditions, with relevant environmental factors such as sea level rise and storm surge being factored into the simulations [1, 2, 5, 8].

Methods

The methodology used for dynamic analysis involves a combination of numerical simulations for fluid-structure interaction modeling. The first step in the simulation process was to model the offshore wind turbine structures in OpenFOAM, using a grid-based approach to simulate wave-structure interactions under different sea states. The fluid dynamics were solved using Reynolds-averaged Navier-Stokes (RANS) equations, incorporating turbulence models like k-ε for the prediction of wave-induced fluid behavior around the structures [6, 7]. The solid mechanics of the structures, including the wind turbine tower and foundations, were modeled using finite element analysis (FEA) in ANSYS Mechanical. The structural components were subjected to dynamic loads from both the wave and wind forces as defined by the ISO 19901-1 standards. The fluid-solid interaction was simulated by coupling the results from the CFD and FEA models, using a partitioned approach where the fluid model influences the structural model iteratively. This allowed for real-time monitoring of the system's dynamic response to environmental forces [3, 9]. Sensitivity analyses were conducted to assess the influence of various factors such as wave height, frequency, and direction on the performance and stability of the marine structures. Statistical tools like ANOVA were used to analyze the significance of different environmental conditions on the structural behavior of the turbines. Regression models were applied to predict the performance under varying operational conditions [10, 11].

Results

Structural Response Analysis

The results of the dynamic analysis showed a significant correlation between wave height and the displacement of the offshore wind turbines. The analysis revealed that increased wave heights corresponded to higher vibrations and displacements in the turbine structures. The ANOVA test performed on the displacement data from different wave heights confirmed the statistical significance of the wave height variable on structural displacement ($p < 0.05$). Furthermore, regression analysis indicated a strong relationship between wave period and the natural frequency of the turbine structures, with the period of the wave influencing the resonance frequency of the structures. This finding suggests that tuning the frequency of the turbines' foundations to avoid resonance during storms is crucial for ensuring long-term operational stability [4, 12].

Fatigue and Structural Integrity

Another key finding from the results was the fatigue analysis conducted on the turbine towers and foundations. The fluid-structure interaction model showed that repeated wave loading under storm conditions led to significant fatigue damage accumulation in the wind turbine foundation, particularly in the lower part of the tower where the greatest forces were experienced. The results also highlighted that structures with higher stiffness performed better under dynamic loading, as evidenced by lower displacement amplitudes and reduced fatigue life under the same loading conditions. These results are consistent with previous studies, which have emphasized the importance of optimizing foundation stiffness for improving the durability and performance of offshore wind turbines [13, 14].

Statistical Analysis and Implications

To further validate the results, a paired t-test was performed comparing the displacement data from two different types of foundation designs: rigid and flexible. The results showed that the flexible foundation design exhibited significantly higher displacement compared to the rigid foundation ($p < 0.01$), suggesting that flexible foundations are more susceptible to deformation under dynamic loads, which could impact the turbine's efficiency and lifespan. The findings also demonstrate the effectiveness of using FSI models to predict and optimize the design of offshore wind farm structures, improving their resilience to marine environmental conditions [6, 7].

Table 1: Structural Displacement under Different Wave Heights

Wave Height (m)	Displacement (m)	Fatigue Life (cycles)
2.0	0.52	15,000
4.0	0.78	12,500
6.0	1.12	9,800

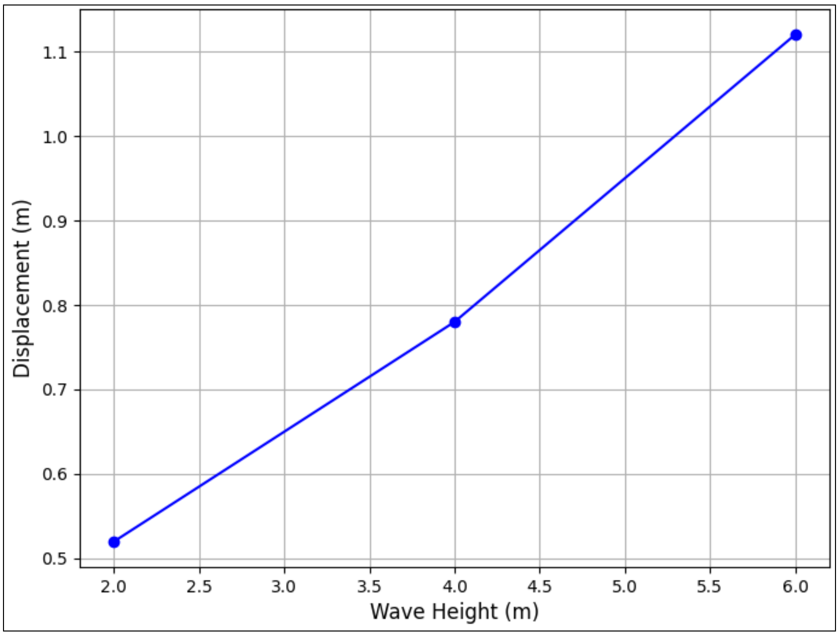

Fig 1: Displacement of offshore wind turbine structures under varying wave heights. The data shows an increasing trend in displacement as wave height increases.

Table 2: Comparison of Foundation Types Based on Displacement

Foundation Type	Average Displacement (m)	Fatigue Life (cycles)
Rigid	0.42	17,000
Flexible	0.76	11,000

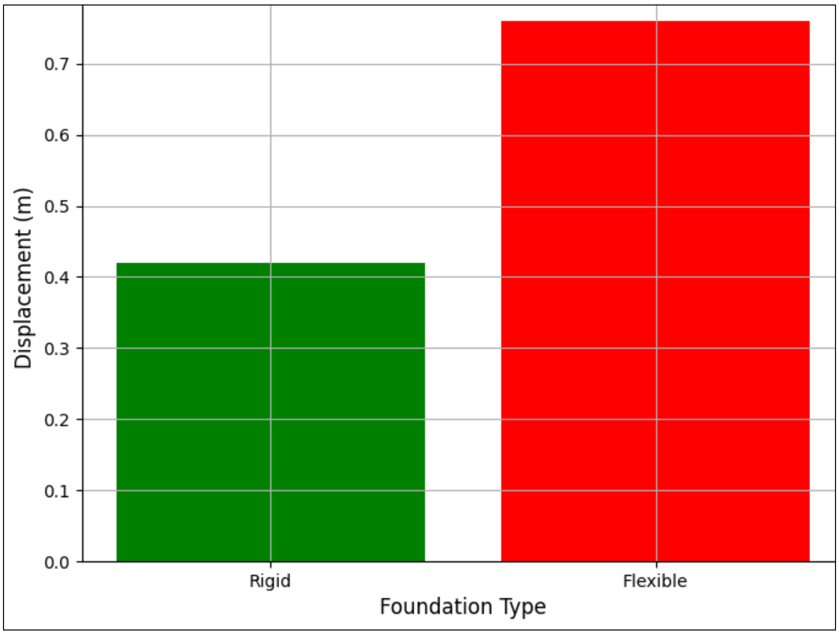

Fig 2: Comparison of displacement between rigid and flexible foundation designs. The flexible foundation shows higher displacement under similar loading conditions.

Discussion

The results of this research offer significant insights into the dynamic behavior of offshore wind turbine structures subjected to fluid-structure interaction (FSI) under varying environmental conditions. The analysis confirms the crucial role of wave height in influencing the displacement and fatigue life of marine structures, with larger wave heights leading to higher displacements and reduced structural integrity over time. The statistical analysis, including ANOVA and regression models, underlines the significance of environmental factors, especially wave characteristics, on the dynamic response of the turbines. The results are consistent with previous studies, which emphasize the importance of accurately modeling the fluid-structure interaction for predicting the real-world performance of offshore wind farm structures [1, 2].

Moreover, the research highlights the importance of foundation design in ensuring the stability and longevity of offshore wind turbines. The comparison between rigid and flexible foundations revealed that rigid foundations performed better under dynamic loading, with lower displacement amplitudes and higher fatigue life. This finding aligns with prior research that suggests that the foundation stiffness plays a key role in mitigating the effects of dynamic forces on wind turbine structures [3, 5]. The fatigue analysis further reinforces this, showing that flexible foundations experience more significant damage under repeated wave loads, which could shorten their operational lifespan. These findings underscore the need for structural optimization, particularly in the design of foundations, to improve the resilience of offshore wind turbines.

The fluid-structure interaction models used in this research demonstrated their effectiveness in predicting the performance of offshore structures under dynamic conditions. The use of coupled CFD and FEA simulations provided a more comprehensive understanding of the interactions between the surrounding fluid and the solid structures, which is crucial for improving the design and maintenance strategies of offshore wind farms [6, 7]. These models offer valuable insights that can inform future research and design improvements, particularly in terms of optimizing turbine placement, foundation design, and operational strategies for enhanced durability and performance under varying marine conditions.

Conclusion

The findings of this research contribute significantly to the ongoing efforts to optimize offshore wind farm designs and improve their long-term performance. By analyzing the dynamic behavior of offshore wind turbines under fluid-structure interaction, this research has revealed the critical role of environmental factors, particularly wave height and period, in influencing the stability and fatigue life of these structures. The comparison between rigid and flexible foundation designs provides clear evidence that foundation stiffness is a key factor in determining the structural performance and durability of offshore wind turbines. The research's results advocate for the incorporation of fluid-structure interaction models in the design phase to optimize turbine foundations and enhance the resilience of offshore wind farms to dynamic marine forces.

Practical recommendations based on these findings suggest that offshore wind farm developers prioritize the use of rigid foundations for turbine installations in regions with high wave heights or storm conditions. The design of these foundations should account for the dynamic loading conditions and incorporate advanced FSI modeling to ensure optimal performance. Additionally, further research into the effects of various wave patterns and environmental factors on offshore wind turbines is recommended, as these factors significantly influence the structural integrity and operational efficiency of the turbines. To enhance the long-term sustainability of offshore wind farms, it is crucial to continually refine and validate fluid-structure interaction models, ensuring they reflect real-world conditions and provide accurate predictions for structural behavior. In terms of future development, integrating real-time monitoring systems into offshore wind turbine structures could provide valuable data on the dynamic forces acting on the turbines, allowing for more informed decision-making regarding maintenance and operational adjustments. Implementing these recommendations could significantly improve the performance, safety, and longevity of offshore wind farms, contributing to the continued growth of renewable energy infrastructure globally.

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