Offshore Wind Turbine Support Structures and Thermal Stress Factors: A Survey

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Abstract

This survey explores the design and performance of offshore wind turbine support structures, focusing on temperature load coefficients and thermal stress factors. These elements are critical in ensuring the reliability and safety of these structures in dynamic marine environments. The study highlights the significance of understanding temperature-induced stresses, which, when combined with wind and wave loads, can affect the fatigue life and serviceability of turbine support systems. The research underscores the importance of integrating temperature load coefficients and thermal stress factors into the design phase to enhance structural resilience. It also examines serviceability and ultimate limit states, emphasizing the need for robust design practices that accommodate both normal and extreme conditions. Advanced computational techniques, such as finite element methods and probabilistic approaches, are discussed for their role in structural analysis, offering insights into optimizing design and performance. The survey concludes by advocating for continued advancements in computational methods and design strategies to address the challenges posed by thermal and mechanical stresses, ensuring the long-term safety and functionality of offshore wind turbine support structures.

1 Introduction

1.1 Overview of Offshore Wind Turbine Support Structures

Offshore wind turbine support structures are vital for the stability and operation of wind energy systems in marine environments, designed to endure harsh conditions while accommodating dynamic loads from the turbines. The monopile, known for its simplicity and cost-effectiveness, is the most common substructure used in offshore wind farms, being driven into the seabed for robust support [1]. Alternative foundations, such as bucket and anchor types, provide specific benefits based on site conditions and water depths [2]. The design often incorporates extra-large (XL) steel plates to manage the substantial loads and stresses encountered offshore [3].

Wind turbine towers, typically slender and flexible, must withstand operational and wind-induced loads. This flexibility can lead to excessive vibrations, necessitating careful management to prevent structural fatigue and ensure long-term reliability [4]. The selection of support structure type and design is influenced by factors including water depth, soil conditions, and the specific requirements of the wind turbine system.

1.2 Importance of Temperature Load Coefficients and Thermal Stress Factors

Temperature load coefficients and thermal stress factors are crucial for the design and safety of offshore wind turbine structures, as the dynamic marine environment exposes them to significant thermal variations that induce stresses. These thermal stresses, combined with oscillatory bending stresses from wind and waves, affect the turbines' fatigue life [1]. Accurate calculation of temperature

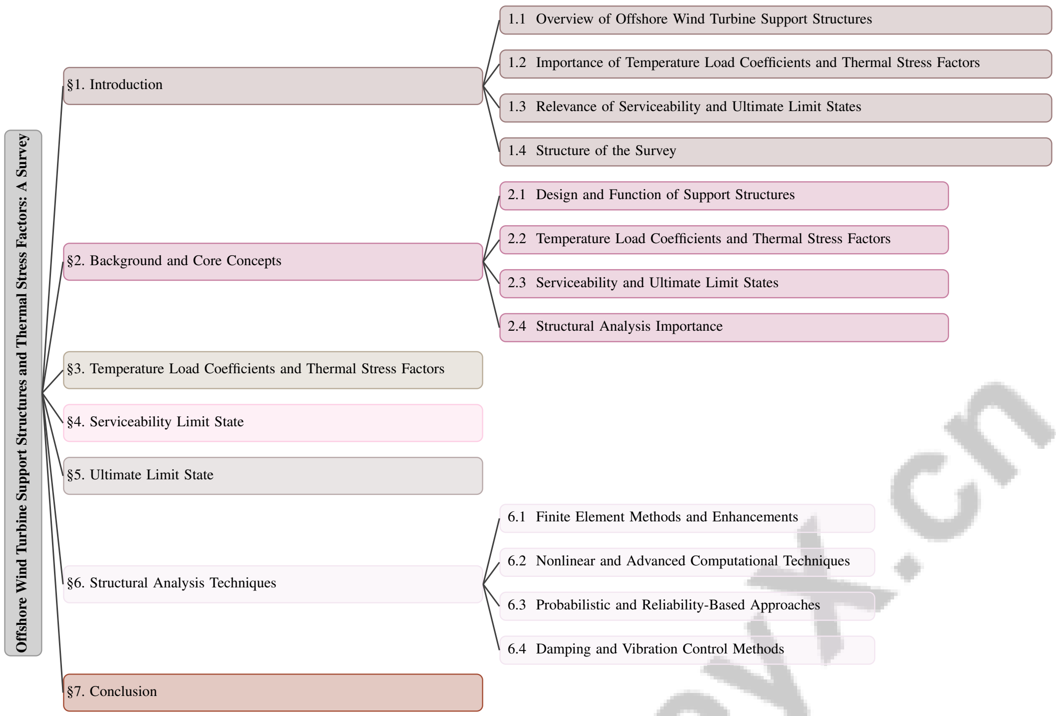

Figure 1: chapter structure

load coefficients is essential for predicting structural responses to thermal fluctuations, thereby mitigating risks of failure.

The importance of these factors is highlighted by the uncertainties in environmental conditions and design parameters [5]. As offshore wind turbines are designed for long-term reliability, robust design practices that account for these uncertainties are critical. Improper management of temperature-induced stresses can worsen vibrations in turbine towers, leading to structural failure and increased maintenance costs [4]. Therefore, integrating temperature load coefficients and thermal stress factors into the design phase is vital for enhancing serviceability and longevity [6].

Moreover, the design and stability of offshore wind turbine foundations must consider complex loadings, including thermal stresses, to maintain structural integrity throughout their operational lifespan [2]. A comprehensive review of structural reliability analysis emphasizes the need to address these factors in future designs, particularly for floating wind turbines, where thermal and mechanical stresses interact more intricately [7].

1.3 Relevance of Serviceability and Ultimate Limit States

Understanding serviceability and ultimate limit states is essential for ensuring the safety and reliability of offshore wind turbine support structures. The serviceability limit state (SLS) focuses on maintaining functionality and user comfort under normal operating conditions, which is critical for offshore wind turbines that must accommodate dynamic responses from aerodynamic, hydrodynamic, structural, and soil damping effects [1]. SLS design is increasingly significant as it governs performance requirements to prevent excessive deformations and vibrations that could impair operational efficiency [8].

Conversely, the ultimate limit state (ULS) assesses the maximum load-carrying capacity of a structure, ensuring it withstands extreme conditions without collapsing. This involves evaluating the structure's resilience against rare events such as severe storms or unexpected load increases. ULS is vital for maintaining overall safety and structural integrity, safeguarding against catastrophic failures. A thorough assessment of both SLS and ULS allows engineers to design support structures that meet immediate operational needs while ensuring long-term durability and safety under various conditions. This dual approach enhances reliability and cost-effectiveness in structural design, addressing real-world complexities while minimizing risks of structural failure [5, 8, 9].

1.4 Structure of the Survey

This survey provides a comprehensive examination of offshore wind turbine support structures, emphasizing thermal stress factors and temperature load coefficients. The introduction establishes the foundational context by highlighting the significance of these factors concerning serviceability and ultimate limit states. Subsequent sections elaborate on background concepts, detailing design, function, and critical aspects pertinent to offshore wind turbine support structures.

The survey progresses to an analysis of temperature load coefficients and thermal stress factors, detailing their impacts on structural behavior and integrity. Following this, serviceability and ultimate limit states are explored, underscoring their importance in safety evaluations. The discussion on structural analysis techniques includes various methods, such as finite element analysis and advanced computational techniques, and their applications in assessing temperature and thermal stress impacts.

The conclusion synthesizes key findings, emphasizing implications for the design and safety of offshore wind turbine support structures and proposing future research directions. This structured approach facilitates a thorough analysis of the intricate relationships between environmental factors and structural performance, playing a crucial role in enhancing the design and reliability of offshore wind energy infrastructure. This is particularly relevant as the industry seeks to optimize turbine support structures and foundation types to meet growing energy demands while ensuring cost-effectiveness and structural integrity [7, 3, 2].The following sections are organized as shown in Figure 1.

2 Background and Core Concepts

2.1 Design and Function of Support Structures

Offshore wind turbine support structures are engineered to endure harsh marine environments, ensuring stability for increasingly large turbines, which presents significant engineering challenges [3]. Foundation selection, divided into fixed and floating systems, is critical. Fixed foundations like monopiles, gravity bases, tripods, and jackets are typically used in shallower waters, while floating foundations, such as suction buckets and tension leg platforms, are favored in deeper waters [2].

Monopiles are preferred in fixed foundations due to their cost-effectiveness and simplicity, yet their fatigue life is highly sensitive to damping variations, requiring careful operational assessments [1]. The fatigue limit state (FLS) is a critical design criterion, especially in Europe, where environmental conditions greatly impact structural integrity [10].

The dynamic behavior of slender and flexible turbine towers necessitates innovative solutions to mitigate vibrations. Techniques like optimizing pendulum mass-spring systems have been proposed to reduce vibrations and enhance stability [4]. The design of offshore wind turbine support structures depends on a complex interplay of environmental conditions, turbine size, and operational requirements, which must be meticulously balanced for reliability and longevity.

2.2 Temperature Load Coefficients and Thermal Stress Factors

Temperature load coefficients and thermal stress factors are crucial for analyzing offshore wind turbine support structures, quantifying the effects of temperature variations on material behavior and structural integrity. Advanced materials like TMC steels are often used to withstand thermal stresses in large turbine support structures [3].

Temperature load coefficients measure the impact of temperature changes on the expansion or contraction of structural elements, critical for turbines where temperature fluctuations can induce stresses affecting fatigue life [1]. The Approximate Damping Influence Method (ADIM) evaluates how varying damping levels, influenced by temperature changes, affect turbine fatigue life, emphasizing the need to consider thermal effects in design processes.

Thermal stress factors describe stresses from temperature gradients within materials, which can be significant when combined with dynamic loads such as wind and waves. Devices like Tuned Mass Dampers (TMDs) help mitigate these stresses by absorbing vibrational energy, reducing vibration levels [6]. Incorporating probabilistic constraints into support structure optimization is crucial for addressing uncertainties affecting performance [5]. By integrating temperature load coefficients

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and thermal stress factors into probabilistic frameworks, engineers can enhance the resilience of offshore wind turbine support structures against thermal and mechanical stresses, ensuring safety and functionality throughout their service life.

2.3 Serviceability and Ultimate Limit States

Serviceability limit state (SLS) and ultimate limit state (ULS) are fundamental for ensuring the safety and reliability of offshore wind turbine support structures. SLS refers to conditions where a structure remains functional and comfortable during normal operations, preventing excessive deflections or vibrations that could impair efficiency [8]. Setting appropriate target reliability values for SLS is vital, influencing design criteria and performance requirements necessary to avoid serviceability issues from thermal stresses and dynamic loads.

ULS pertains to a structure's maximum load-carrying capacity, ensuring resilience against extreme conditions without collapsing. This evaluation includes a structure's ability to endure rare events, such as intense storms or unexpected load surges. Traditional design methods, like allowable working stress design, often fall short in accurately determining safety margins for complex structures like box girders, underscoring the need for robust ULS assessment methodologies [9]. A comprehensive understanding of interactions between environmental loads and structural responses is essential for offshore wind turbine applications.

Recent advancements in structural reliability assessment methods have enabled more nuanced evaluations of ULS for offshore wind turbines. By comparing various probabilistic approaches, researchers aim to enhance methodologies for ULS assessment, ensuring structures maintain integrity under extreme loading scenarios [11]. This dual focus on SLS and ULS allows engineers to design support structures that meet immediate functional requirements while ensuring long-term durability and safety, thereby enhancing the overall reliability of offshore wind energy systems.

2.4 Structural Analysis Importance

Structural analysis is vital for evaluating temperature load and thermal stress effects on offshore wind turbine support structures. The complexity of these structures in dynamic marine environments necessitates sophisticated analytical approaches to ensure structural integrity and safety. Traditional deterministic finite element methods often struggle with uncertainties inherent in such complex systems. The Sample-based Stochastic Finite Element Method (S-SFEM) effectively represents these uncertainties, enhancing structural assessment precision [12].

Advanced computational techniques, such as the NURBS-Enhanced Finite Element Method (NE-FEM), enable accurate modeling of complex geometries, crucial for fluid-structure interaction analyses in offshore settings [13]. The finite cell method (FCM) further improves structural analysis by examining intricate geometries without conventional meshing requirements [14]. These advancements are essential for capturing nuanced interactions between environmental loads and structural responses.

In fatigue analysis, methodologies like rainflow counting applied to stress time histories from time-domain finite element simulations are critical for assessing fatigue damage, highlighting the computational demands of such evaluations [1]. Nonlinear finite element methods are also vital for optimizing designs under ultimate loads, ensuring structures withstand extreme conditions [9].

The Hierarchical Structural Analysis Method (HSAM) leverages the natural hierarchical structure of equation-oriented models to reduce computational complexity and improve analysis efficiency, providing a structured approach to managing offshore wind turbine support structures' complexities [15]. Additionally, the framework by Igwemezie et al. categorizes research based on turbine size, material types, and design methodologies, offering a comprehensive basis for structural analysis [3].

Optimization approaches, such as integrating genetic algorithms with finite element models, have shown potential in enhancing structural performance, as evidenced by experiments on wind towers [4]. The Differentiable Structural Analysis Framework (DSAF) automates gradient computation, enabling rapid and precise optimization of complex structural systems, facilitating more efficient design processes [16].

The significance of structural analysis in assessing temperature load and thermal stress impacts lies in its ability to integrate advanced computational methods with robust design frameworks. This integration is crucial for ensuring that offshore wind turbine support structures maintain their structural integrity and operational functionality amidst challenging environmental conditions, such as extreme wind and wave loads. By addressing the geotechnical and structural challenges associated with foundation design, this approach enhances the resilience of these structures and significantly advances the development and reliability of offshore wind energy infrastructure, ultimately supporting the transition to a low-carbon energy system [5, 3, 2].

In recent studies, the significance of temperature load coefficients and thermal stress factors in the design of offshore wind turbine support structures has gained considerable attention. Understanding the hierarchical relationship between these variables is crucial for ensuring the structural integrity and longevity of these systems. Figure 2 illustrates the hierarchical structure of temperature load coefficients and thermal stress factors, detailing their impact on offshore wind turbine support structures. This figure categorizes the influence of temperature variations, methodologies for coefficient calculation, and the role of thermal stress factors in maintaining structural integrity. By analyzing these components, researchers can develop more robust designs that effectively mitigate the risks associated with thermal fluctuations.

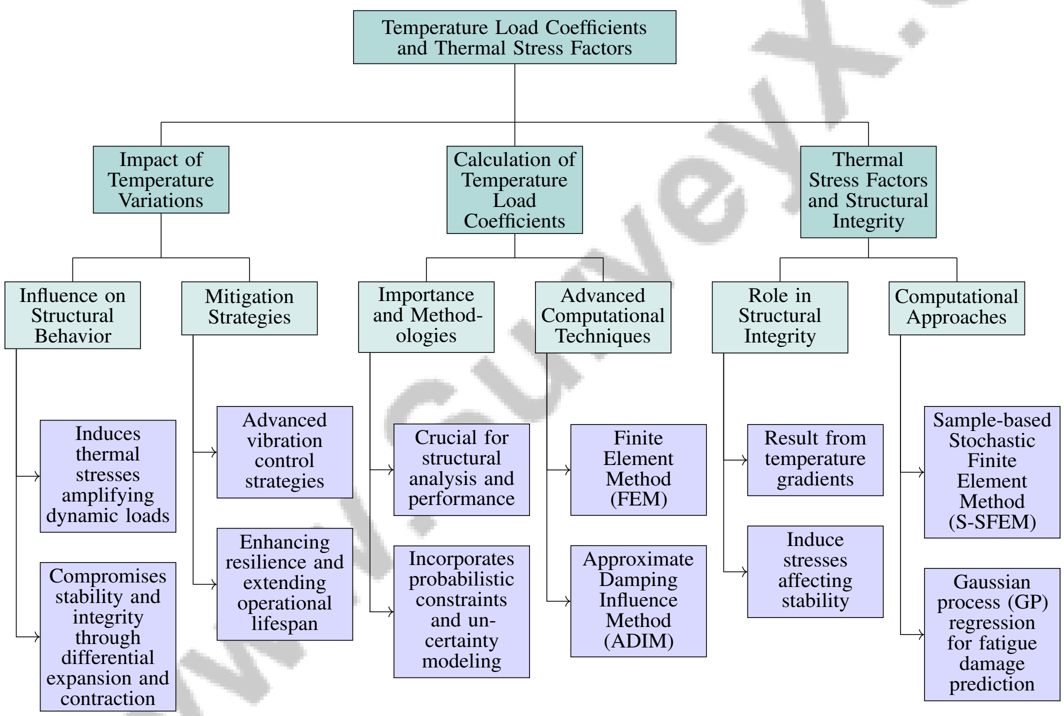

Figure 2: This figure illustrates the hierarchical structure of temperature load coefficients and thermal stress factors, detailing their impact on offshore wind turbine support structures. It categorizes the influence of temperature variations, methodologies for coefficient calculation, and the role of thermal stress factors in structural integrity.

3 Temperature Load Coefficients and Thermal Stress Factors

3.1 Impact of Temperature Variations

Temperature variations significantly influence the structural behavior of offshore wind turbine support structures by inducing thermal stresses that can amplify existing dynamic loads. Such fluctuations, due to environmental changes, lead to differential expansion and contraction in materials, potentially compromising stability and integrity. Ghassempour et al. highlight that variable wind conditions can exacerbate thermal stress effects in offshore horizontal-axis wind turbines (HAWTs) [6]. This interplay between thermal and dynamic loads necessitates a comprehensive approach to structural design and analysis, ensuring that support structures accommodate these variations without compromising functionality.

Advanced vibration control strategies, as explored by Colherinhas et al., are essential for mitigating the adverse effects of temperature variations [4]. By integrating such strategies, engineers can enhance the resilience of support structures, improving structural integrity and extending operational lifespan by reducing fatigue-induced failures. Addressing temperature variations through innovative design and control methodologies is crucial for advancing the reliability of offshore wind energy systems.

3.2 Calculation of Temperature Load Coefficients

The calculation of temperature load coefficients is crucial for the structural analysis of offshore wind turbine support structures, significantly influencing design integrity and operational performance under varying thermal conditions. This is increasingly vital as wind turbines grow in size and complexity, necessitating design methodologies that incorporate probabilistic constraints and uncertainty modeling to optimize structural resilience and cost-effectiveness [5, 7, 3]. These coefficients quantify the impact of temperature changes on structural elements, guiding engineers in predicting and mitigating potential thermal stresses by assessing the thermal expansion properties of materials used in support structures.

Advanced computational techniques, particularly the finite element method (FEM), are essential for calculating these coefficients. FEM enables detailed modeling of structural components, considering thermal properties and boundary conditions specific to offshore environments [3]. By simulating various thermal scenarios, engineers can evaluate potential impacts on structural integrity and identify critical areas vulnerable to thermal stress.

The Approximate Damping Influence Method (ADIM) assesses temperature-induced damping variations on the fatigue life of offshore wind turbines [1]. This method underscores the importance of incorporating temperature load coefficients into design and analysis processes to ensure long-term reliability. Additionally, integrating probabilistic approaches in coefficient calculations accounts for uncertainties in material properties and environmental conditions, enhancing structural design robustness [5].

Accurate temperature load coefficient calculations are essential for improving the design and operational efficiency of offshore wind turbine support structures, directly influencing structural reliability and fatigue life under varying environmental conditions and loading scenarios. This optimization is critical in the offshore wind industry's efforts to reduce costs and enhance the performance of increasingly larger turbines, where precise thermal modeling can lead to significant advancements in material selection and structural integrity [5, 7, 3, 1]. By leveraging advanced computational methods and probabilistic considerations, engineers can effectively tackle challenges posed by thermal variations, ensuring the safety and durability of these components in harsh marine environments.

3.3 Thermal Stress Factors and Structural Integrity

Thermal stress factors are pivotal in determining the structural integrity of offshore wind turbine support structures. These factors result from temperature gradients within materials, leading to differential expansion and contraction that induce additional stresses affecting overall stability. The reliability of these structures under various loading conditions and uncertainties is a core issue influencing their design and operational safety [7].

Advanced computational methods, such as the Sample-based Stochastic Finite Element Method (S-SFEM), are developed to address these challenges by iteratively computing deterministic responses and their corresponding random variable coefficients, thereby efficiently managing high-dimensional stochastic problems [12]. Such capabilities are vital for maintaining structural integrity under uncertain conditions, allowing for a more accurate assessment of thermal stress impacts.

Additionally, surrogate models created using Gaussian process (GP) regression provide a framework for predicting load-induced fatigue damage, facilitating fatigue life evaluation by offering a more efficient means of simulating and analyzing the effects of thermal and mechanical loads on structural components [10]. By utilizing these advanced computational techniques, engineers can better predict and mitigate the adverse effects of thermal stress factors on the structural integrity of offshore wind turbine support structures.

A comprehensive understanding of thermal stress factors is essential for effectively designing support structures, particularly for offshore wind turbines, which must withstand complex interactions of environmental loads—such as wind and wave forces—and thermal variations. This knowledge enables engineers to optimize structural integrity and reliability, ultimately enhancing the longevity and cost-effectiveness of these systems [3, 16, 5, 8, 1]. By incorporating robust analytical methods and considering uncertainties, the resilience and reliability of these structures in demanding marine environments can be significantly improved.

4 Serviceability Limit State

The serviceability limit state is crucial for evaluating the performance and operational reliability of offshore wind turbine support structures. This section delves into various serviceability criteria essential for designing and assessing these structures, emphasizing the need for comprehensive evaluation methods to address unique operational challenges. Key aspects include vibration control and damping enhancement, which are vital for understanding factors affecting serviceability and strategies to mitigate potential issues. The subsequent subsection will provide an in-depth examination of specific serviceability criteria relevant to offshore wind turbine support structures, setting the stage for a thorough analysis of challenges in maintaining operational integrity.

4.1 Serviceability Criteria

Assessing serviceability criteria for offshore wind turbine support structures is crucial for ensuring functionality and comfort during normal operations. This evaluation addresses structural integrity challenges associated with the design of large wind turbine support structures, which face complex loading conditions and environmental influences [3]. A primary concern is managing excessive vibrations from wind-wave loading, which can impair turbine efficiency. The application of Tuned Mass Dampers (TMDs) has proven effective in mitigating these vibrations by adapting to varying operational conditions, thereby enhancing structural serviceability [6].

Enhanced damping plays a pivotal role in extending the fatigue life of offshore wind turbines, contributing to improved serviceability. Rezaei et al. demonstrate that increased damping significantly prolongs the lifespan of these structures by reducing the impact of dynamic loads [1]. Advanced computational methods, such as the NURBS-Enhanced Finite Element Method (NEFEM), provide improved accuracy and stability in fluid-structure coupling, essential for evaluating serviceability under normal operating conditions [13].

The serviceability criteria for offshore wind turbine support structures encompass a comprehensive approach integrating vibration control, damping enhancement, and advanced computational techniques. These established criteria ensure that structural integrity and operational efficiency are maintained, which is crucial for enhancing the long-term reliability and overall performance of renewable energy installations, especially given the increasing size of turbines and the challenges posed by their support structures [7, 3, 2].

4.2 Examples of Serviceability Issues

Serviceability issues in offshore wind turbine support structures often arise from complex interactions between thermal stresses and dynamic loads, posing challenges to operational efficiency and structural integrity. Excessive vibrations induced by thermal stresses can exacerbate the dynamic response of structures under wind and wave loading, potentially leading to increased fatigue damage and reduced service life [4].

Temperature gradients within structural materials can cause differential expansion and contraction, introducing additional stresses that affect serviceability. Ghassempour et al. underscore the importance of addressing these thermal effects, as they can critically impact structural behavior, leading to issues such as misalignment or excessive deflections [6].

The integration of advanced damping mechanisms, such as TMDs, is essential for mitigating the adverse effects of thermal and dynamic loads on serviceability. These devices absorb vibrational energy and stabilize the structure, ensuring functionality and efficiency under varying environmental conditions [1]. By implementing effective vibration control strategies and addressing thermal stress challenges, engineers can enhance the serviceability and longevity of offshore wind turbine support structures.

5 Ultimate Limit State

5.1 Evaluation Methods for Ultimate Limit State

Benchmark	Size	Domain	Task Format	Metric
ULS-Benchmark[11]	1,000	Offshore Wind Turbine Reliability Assessment	Extreme Response Estimation	Maximum Flapwise Blade Root Bending Moment

Table 1: This table presents a benchmark used for evaluating the reliability of offshore wind turbine support structures under extreme conditions. It details the size, domain, task format, and metric employed in the ULS-Benchmark, providing insights into the methodologies applied for structural reliability assessment.

Evaluating the ultimate limit state (ULS) of offshore wind turbine support structures is crucial for ensuring their safety and structural integrity under extreme conditions. This evaluation employs probabilistic and deterministic approaches, each offering unique insights into structural performance and reliability. The probabilistic framework for structural reliability analysis (SRA), as described by Jiang et al., accounts for uncertainties in loads and material properties, providing a comprehensive risk assessment beyond traditional deterministic methods [7]. Reliability-based design optimization (RBDO), as proposed by Stieng et al., incorporates probabilistic constraints to balance reliability with design mass reduction, optimizing safety and cost-effectiveness [5]. Van der Meer et al. further enhance evaluation by integrating economic optimization within the reliability framework, aligning structural performance with economic goals [8].

Deterministic approaches, such as the Ultimate Limit State Design Method (ULSDM), ensure that the maximum load-carrying capacity exceeds applied loads with a sufficient safety margin, as emphasized by Lee et al. [9]. This method is vital for assessing structural strength and stability under extreme loading conditions. Advanced computational techniques, including the Differentiable Structural Analysis Framework (DSAF), significantly enhance optimization speed and solution quality across various structural design challenges [16]. Gaussian process (GP) surrogate models, demonstrated by Wilkie et al., efficiently evaluate fatigue reliability by modeling fatigue damage data from time-history analyses [10].

The impact of excessive vibrations on structural safety, especially with dynamic tuning mechanisms like Tuned Mass Dampers (TMDs), is critical in ULS evaluations [6]. Rezaei et al.'s method assesses damping effects efficiently, potentially reducing turbine design costs [1]. Benchmark tests by Wang et al. compare established methods like environmental contours with innovative approaches, such as the sequential sampling method using Gaussian processes, providing valuable insights into ULS evaluation techniques [11]. Table 1 provides an overview of a representative benchmark utilized in the evaluation of ultimate limit states for offshore wind turbine structures, highlighting the key parameters and metrics involved in the assessment process. These comprehensive methods ensure the integrity and safety of offshore wind turbine support structures under extreme conditions, advancing offshore wind energy infrastructure.

5.2 Role of Thermal Stress Factors

Thermal stress factors significantly influence the ultimate limit state (ULS) assessment of offshore wind turbine support structures, affecting structural dynamics and safety margins. These stresses, arising from temperature-induced changes within materials, exacerbate dynamic loads and impact stability. Igwemezie et al. emphasize the importance of incorporating thermal stress factors in ULS assessments, particularly regarding the dynamic behavior of support structures under varying operational conditions [3].

Integrating thermal stress considerations into the Ultimate Limit State Design Method (ULSDM) provides a comprehensive approach to evaluating the ultimate strength and safety margins of these structures. Lee et al. note that this integration enhances the accuracy of determining ultimate strength

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and safety margins, optimizing material usage and achieving cost savings [9]. By factoring in thermal stress, engineers can maintain structural integrity and safety under extreme environmental conditions, enhancing the reliability and efficiency of offshore wind energy systems.

Advanced computational techniques and robust design frameworks facilitate the effective evaluation of thermal stress impacts on the ULS, leading to the development of resilient support structures capable of withstanding environmental loads and temperature variations. This comprehensive approach ensures that offshore wind turbine support structures are designed to endure thermal stresses and other environmental challenges, significantly enhancing safety and durability in demanding marine environments. Research into advanced materials, such as thermo-mechanical controlled process (TMCP) steels, and innovative foundation designs, including monopiles and bucket foundations, is crucial for improving structural integrity and long-term performance as the industry scales turbine capacities to meet future energy demands [3, 2].

6 Structural Analysis Techniques

6.1 Finite Element Methods and Enhancements

Finite element methods (FEM) are pivotal for analyzing offshore wind turbine support structures, addressing complex interactions between environmental loads and structural responses. Innovations like the Sample-based Stochastic Finite Element Method (S-SFEM) have improved FEM by incorporating stochastic analyses to enhance structural reliability [12]. The NURBS-Enhanced Finite Element Method (NEFEM) advances fluid-structure interaction analyses with a unified spline interface, improving simulation accuracy and stability [13]. The Finite Cell Method (FCM) is notable for its high convergence rates and effectiveness in nonlinear structural analysis, suitable for offshore applications with complex geometries [14].

In fatigue analysis, Rezaei et al. introduced a method leveraging reference time-domain analysis to predict fatigue life across varying damping levels, optimizing fatigue assessments [1]. Genetic algorithms further refine Tuned Mass Damper (TMD) design parameters, enhancing vibration mitigation and structural integrity [4]. The Hierarchical Structural Analysis Method (HSAM) improves finite element applications by analyzing models layer by layer to reveal structural singularities [15]. The Differentiable Structural Analysis Framework (DSAF) employs reverse-mode automatic differentiation to streamline structural design optimization [16].

These FEM advancements facilitate accurate assessments of offshore wind turbine support structures, addressing complex environmental loads and enhancing structural integrity and longevity to meet future energy demands and reduce greenhouse gas emissions [1, 3, 2].

6.2 Nonlinear and Advanced Computational Techniques

Nonlinear and advanced computational techniques are crucial for analyzing the dynamic interactions between environmental loads and offshore wind turbine support structures. Igwemezie et al. underscore the need for these methods to evaluate long-term material durability under extreme conditions, especially for floating turbine designs [3]. NEFEM's partitioned strategy with strong coupling enhances fluid-structure interaction analyses [13], while the Finite Cell Method (FCM) manages complex geometries without conventional meshing, despite challenges in nonlinear stability and accuracy [14]. HSAM efficiently analyzes hierarchical structures, revealing structural singularities beneficial for nonlinear analyses [15].

Integrating these techniques enhances the reliability and performance of offshore wind turbine support structures, enabling precise assessments of structural integrity under various load conditions and facilitating the design of resilient support systems for extreme environments [10, 3, 5, 7, 11].

6.3 Probabilistic and Reliability-Based Approaches

Probabilistic and reliability-based approaches are essential for evaluating offshore wind turbine support structures, managing uncertainties in environmental conditions and material properties. These methods improve safety evaluations and enable cost-effective design optimizations through techniques like Gaussian process regression and gradient-based optimization [5, 11, 10, 7]. Reliability-based design optimization (RBDO) incorporates probabilistic constraints to ensure safety compliance while minimizing costs, with Jiang et al. extending these methods to floating wind turbines [7].

Economic considerations in reliability analysis, as discussed by Van der Meer et al., align with probabilistic approaches for cost-effective structural integrity evaluations [8]. Advanced computational techniques like NEFEM enhance reliability assessments by maintaining consistent geometric representations, reducing numerical errors, and improving stability [13]. Wang et al.'s benchmark study highlights the sequential sampling method as an efficient alternative to traditional reliability assessments, offering similar accuracy with improved computational efficiency [11].

6.4 Damping and Vibration Control Methods

Method Name	Control Techniques	Optimization Strategies	Environmental Adaptation
TMD[6]	Tuned Mass Dampers	Probabilistic Design Optimization	Dynamic Environmental Conditions
ADIM[1]	Time-domain Simulations	Efficient Approximate Method	Dynamic Environmental Conditions
GA-TMD[4]	Tuned Mass Dampers	Genetic Algorithms	Environmental Changes
NEFEM[13]	-	-	-

Table 2: Summary of various damping and vibration control methods used in offshore wind turbine support structures, highlighting control techniques, optimization strategies, and environmental adaptation capabilities. The table encapsulates the methodologies and their specific focus areas, providing insights into their applications and effectiveness in dynamic marine environments.

Damping and vibration control are critical for maintaining the stability of offshore wind turbine support structures under dynamic environmental conditions. Tuned Mass Dampers (TMDs) effectively mitigate vibrations from wind and wave-induced loads, enhancing structural stability by absorbing vibrational energy [6]. Rezaei et al. demonstrate that increased damping significantly extends fatigue life, improving serviceability and reducing maintenance costs [1]. Genetic algorithms optimize TMD design parameters, further enhancing vibration control and structural reliability [4].

Advanced computational techniques like NEFEM facilitate accurate fluid-structure interaction analyses, essential for evaluating damping strategies in offshore environments [13]. This method enhances simulation stability and precision, allowing detailed assessments of vibration control measures. Table 2 provides a comprehensive overview of the damping and vibration control methods applied to offshore wind turbine support structures, detailing the control techniques, optimization strategies, and environmental adaptation mechanisms employed.

Implementing damping and vibration control methods is vital for the structural integrity and operational efficiency of offshore wind turbine support structures. By leveraging advanced technologies and computational methods, engineers can effectively address complexities from dynamic environmental loads, enhancing safety and longevity in challenging marine environments. This approach includes probabilistic design optimization and surrogate modeling, facilitating efficient reliability assessments and the development of robust support structures, ultimately leading to cost savings and improved performance in harsh conditions [10, 3, 5, 8, 1].

7 Conclusion

This survey delves into offshore wind turbine support structures, underscoring the pivotal role of temperature load coefficients and thermal stress factors in ensuring their design efficacy and safety. The integration of advanced materials and optimized design strategies emerges as essential for bolstering resistance to fatigue and environmental challenges. Employing reliability-based design optimization (RBDO) methodologies proves indispensable for achieving robust and efficient designs with feasible computational demands. Advanced computational techniques, notably the Sample-based Stochastic Finite Element Method (S-SFEM), offer significant promise in addressing uncertainty quantification for complex, large-scale problems. Furthermore, the application of Gaussian process (GP) regression has effectively reduced computational efforts while enabling thorough reliability assessments across diverse locations.

Looking ahead, research should focus on enhancing the stability of the Finite Cell Method (FCM) for nonlinear applications and its synergy with other computational approaches. The integration of machine learning models with optimization frameworks, coupled with improvements in computational

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efficiency through parallelization, presents a fertile ground for exploration. Additionally, experiments employing genetic algorithms have successfully mitigated vibration levels in wind turbine towers, demonstrating the efficacy of proposed vibration control strategies. This survey highlights the imperative to advance computational methodologies and design approaches to secure the long-term reliability and safety of offshore wind turbine support structures amidst thermal and mechanical stresses.

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