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Review on Advancements and Challenges of Offshore Floating Wind Turbine Platforms

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Abstract: *The increasing global demand for renewable energy has significantly accelerated the development of floating offshore wind turbine (FOWT) platforms, particularly as wind energy resources expand into deeper waters. This paper provides a comprehensive overview of the evolution of floating platforms, examining traditional designs such as spar, barge, semi-submersible, and tension leg platforms (TLP), along with recent advancements in hybrid and nature-inspired structures. Key structures innovations, including the integration of wave energy converter and biomimetic designs, are highlighted for their contributions to enhanced stability, cost efficiency, and energy output. Furthermore, the paper also reviews recent advancements in platform optimization techniques, including genetic algorithms, structural and analytical optimization methods, which improve platform stability and hydrodynamic performance. Finally, various attitude control and stability regulation methods, such as active and semi-active control strategies, as well as data-driven and model predictive approaches, are explored for their potential to improve stability and energy efficiency under dynamic environmental conditions. This review aims to provide valuable insights into the ongoing advancements and challenges in FOWT platform design, offering guidance for future research and large-scale deployment.*

Keywords: *Floating Offshore Wind Turbine (FOWT), Platform Structure, Stability Control, Optimization Method, Hybrid Energy Integration*

1. Introduction

With the increasing consumption of fossil fuels, the problem of energy depletion and environmental pollution has become increasingly prominent. The transition to energy, replacing traditional fossil fuels, has thus become a pressing global demand [1]. Driven by the global transition to energy and the "dual carbon goals", the importance of renewable energy has become even more prominent, with wind power emerging as a leading direction for future energy development. According to the statistics of the Global Wind Energy Council (GWEC) [2], global offshore wind power installations grew by 10.8 GW in 2023, reaching a total installed capacity of 75.2 GW. GWEC forecast that by 2030, the global offshore wind power capacity will reach 380 GW, indicating the significant potential for growth within the offshore wind industry. Indeed, the development of wind power presents a wide range of economic and environmental benefits. Given that much of the available wind energy remains untapped, the future potential for offshore wind power remains immense.

Offshore wind power has the advantages over onshore wind power, including higher wind energy density, longer utilization time, vast ocean areas, fewer space constraints, conservation of land resources, and minimal impact on human daily life [3]. Additionally, the wind resources in offshore environments typically surpass those of onshore sites, driving a gradual shift in wind power utilization from land to ocean, and it is showing a trend of accelerated development [4]. However, as offshore energy development moves into deep sea (beyond 60 m in depth), traditional fixed platforms face technical challenges, such as increased material usage, high construction costs, and difficulties in installation. Therefore, the floating platform technology has emerged as an attractive alternative for deep-sea wind energy development [5]. Drawing on experiences from the offshore oil and gas (O&G) industry, floating wind turbine systems overcome the limitations of fixed platforms, offering new opportunities for harnessing deep-sea wind resources [6].

The integrity of the floating platform is crucial for the safe, stable, and efficient operation of wind turbines. However, the development of FOWT platforms faces several challenges, including structural instability under extreme weather conditions, high material and manufacturing costs, complex

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hydrodynamic interactions, and the need for efficient energy transmission solutions. Additionally, optimizing mooring systems and reducing platform motion while maintaining cost-effectiveness remains a significant technical hurdle. Given these challenges, this paper first introduces several traditional FOWT platform designs, followed by a review of recent advancements in multi-functional and hybrid platform structures that aim to enhance stability and energy efficiency. It then explores various optimization methods, such as genetic algorithms and analytical methods, that improve hydrodynamic performance and structural reliability. Finally, the paper examines recent progress in motion control and stability regulation methods, including active and semi-active strategies, as well as predictive control approaches that leverage data-driven models. By identifying existing limitations and discussing innovative solutions, this study provides valuable insights into future optimization efforts, guiding the design of more resilient, cost-effective, and high-performance floating wind platforms.

2. Innovation and Development of Floating Platform Structure

2.1 Early Floating Flatform Structures

Floating platforms have been utilized for offshore O&G applications over the past 60–70 years, demonstrating the technology proven reliability and providing valuable lessons learned throughout this period. As a result, several floating platform typologies from the O&G have been adopted for FOWT [7]. Given the critical importance of stability, traditional FOWT platforms are categorized into four primary types: (1) Spar, (2) Barge, (3) Semi-submersible platform (Semi-sub) and (4) TLP. Examples of each type are presented in Fig.1.

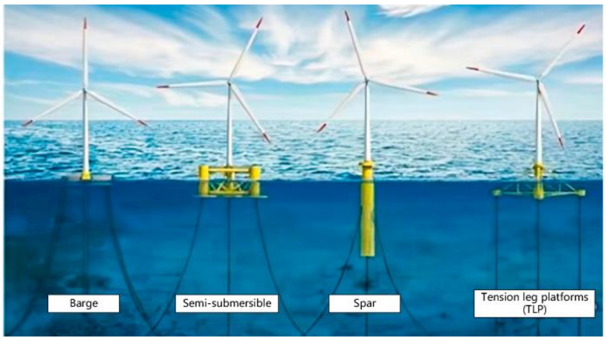

Fig. 1 Types of platforms used for FOWTs [8]

Tab.1 Typical advantages and disadvantages of different types of FOWT platform

	Advantages	Disadvantages
Spar	•Simple design and manufacturing process •Proven in commercial operations (30 MW capacity currently in use) •Minimal heave motion, enhancing stability in deep waters	•Requires deep water (typically over 100 m) for installation •Complex transportation and installation due to large draft •High fatigue load on the base, increasing maintenance needs
Barges	•Independent of water depth, allowing for flexible deployment •Provides a stable platform with lower pitch and roll motion •Larger deck space facilitates easier maintenance and equipment placement	•Sensitive to wave fluctuations, reducing overall stability •Not ideal for regions with high sea state variability •Increased motion response under rough sea conditions
Semi-sub	•Does not require deep-water ports or specialized equipment for deployment •Moderate stability with reduced tilt due to larger surface area	•More complex manufacturing process compared to spar-type platforms •Larger seabed footprint due to multiple supporting columns •Greater heave motion compared to alternative designs
TLP	•Minimal heave and pitch motion, enhancing stability •Small seabed footprint reduces environmental impact •Can be deployed in various water depths, offering flexibility in site selection •Lightweight structure requires less material, lowering costs	•Requires specialized vessels for installation due to instability during towing •High-cost mooring lines and anchors due to vertical load demands •Limited large-scale deployment, with low Technology Readiness Level (TRL) for FOWTs

Edwards et al. [5] conducted an early analysis (Tab.1) of four fundamental FOWT concepts, demonstrating their relative advantages and limitations. Spar platforms achieve stability through a deep-draft cylindrical structure with ballast at the bottom. The low center of gravity and buoyancy interaction enhance the platform's stability, making it less susceptible to the effects of currents. However, it requires deep waters (typically over 100 m), making them unsuitable for shallow regions [5–9].

Barge uses waterplane stabilization. A typical barge features a floating wide, shallow platform [5]. Barge-type platform leverages the buoyancy principle to counteract gravity, offering ease of installation and lower costs. However, it is more sensitive to seawater fluctuations, making it less stable. It is generally suitable only for areas where wave and current fluctuations are relatively mild [9-11].

Semi-subs offer substantial stability due to their large waterplane area. Tilting of the platform increases buoyancy on the leeward side, facilitating the restoration of equilibrium. The inclusion of heave plate mitigates vertical motion, while their design enables a shallow draft. They balance stability and practicality through multiple submerged columns connected by bracings, reducing tilt and wave-induced motion [7-18].

TLPs achieve stability through mooring systems, where a submerged body is tethered to the seabed by mooring lines, with a central column supporting the wind turbine. The high tension in the mooring lines restricts the platform's movement, allowing it to behave almost like a rigid structure. This enhanced stability contributes to more consistent power production and improved overall system reliability [9].

2.2 Innovations in Platform Design and Structures

As offshore wind energy expands into deeper waters, the limitations of traditional floating offshore wind turbine (FOWT) platforms have become increasingly apparent. To address these challenges, researchers have developed innovative platform designs (Fig. 2) that enhance stability, efficiency, and adaptability. This section examines recent advancements in FOWT platform structures, highlighting key innovations, their advantages and limitations, and subsequent optimizations.

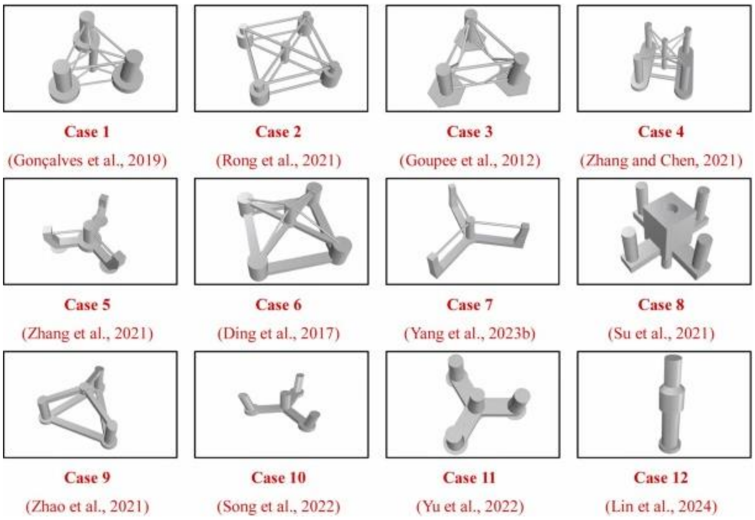

Fig. 2 Diagram of 12 structures [10]

Initial FOWT platforms were largely based on conventional designs, yet they exhibited significant limitations in stability under extreme conditions and structural efficiency. In response, Jiang et al. [11] introduced the stepped short-spar platform (SJTU-S4) (Fig. 3(a)), which demonstrated feasibility in moderate water depths and provided an alternative to traditional deep-sea spar platforms. Pham et al. [12] further enhanced spar-type platforms by incorporating a moonpool, which effectively mitigated dynamic responses to horizontal and rotational motions. The concept of a fully submersible platform (FSP) emerged as a promising alternative to traditional semi-sub models. Zhang et al. [3] developed an FSP integrating vertical carbon fiber reinforced polymer (CFRP) tendons and circumferential catenary chains, enhancing structural redundancy under extreme conditions such as typhoons. Inspired by the combined characteristics of spar, semi-submersible, and tension-leg platforms (TLPs), this design exhibited superior resistance to mooring line failures, ensuring operational stability in harsh environments. Similarly, Zhang et al. [13] introduced an inclined-column fully submersible platform (Fig. 3(b)) that reduced steel costs by 12.8% compared to conventional semi-sub designs while maintaining ease of towability. Meng et al. [14] proposed an advanced semi-sub platform (Fig. 3(c)) featuring optimized ballast tank and heave plate placements, outperforming the VolturnUS-S platform [15] (Fig. 3(d)) in

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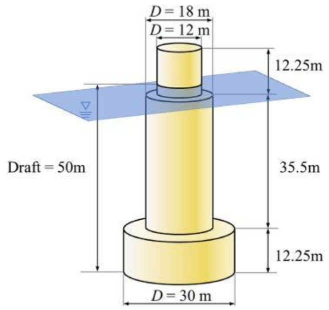
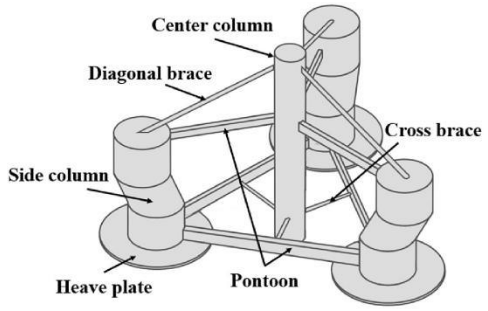
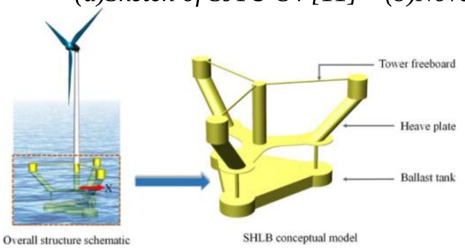
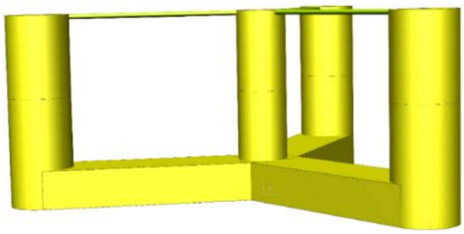
mitigating platform motion caused by wind loads, wave forces, and 1P effects. These innovations significantly improved stability and natural frequency characteristics.





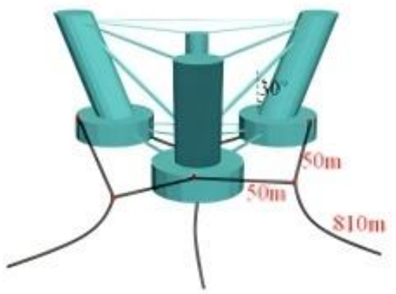
(a)Sketch of SJTU-S4 [11]   (b)Novel FOWT platform design concepts [13]

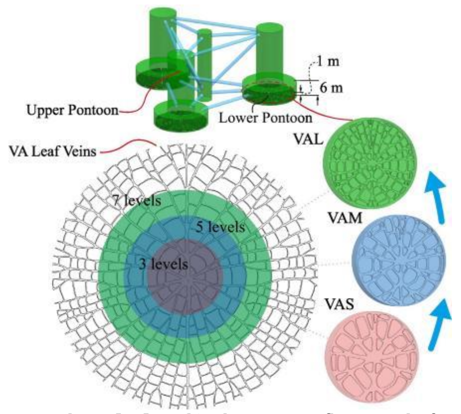




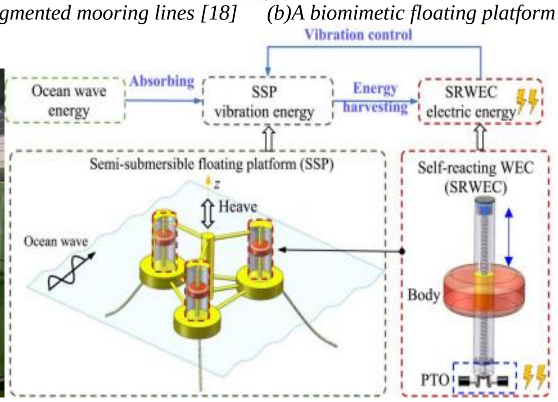
(c)Diagram of the SHLB design model [14]   (d)The UMaine VolturnUS-S foundation [15]

Fig. 3 Early innovations in FWTO platform structure





(a)A new platform with inclined columns and multi-segmented mooring lines [18]   (b)A biomimetic floating platform [6]

(c)Photo of the FOWT-OWC platform   (d) SSP-SRWEC [20]

Fig. 4 Several novel floating platform structure diagram

With advancements in technology, hybrid platforms that combine multiple stabilization techniques have garnered increasing attention. Edwards et al. [16-17] reviewed several hybrid models, such as the Cobra Semi-Submersible Spar Platform (Cobra Semi-Spar), Telescopic Wind Platform (Telwind), Semi-Submersible and Tension Leg Wind Tower (SSTLWT), X1 Wind Floating Wind (X1Wind) platforms. These models integrate semi-sub, spar and TLP elements to enhance stability. Similarly, Liu et al. [18] introduced a semi-sub FOWT platform (Fig. 4(a)) featuring inclined columns and multi-segmented mooring lines, significantly reducing surge and heave motions while improving stability. However, the additional structural reinforcements required for inclined columns increased material costs. Additionally, nature-inspired designs have also emerged as a promising approach to optimizing floating platforms. Liu et al. [6] proposed a biomimetic platform (Fig. 4(b)) modeled after the Victoria Amazonica (VA) plant. By integrating leaf venation structures, this design reduced pitch amplitude by 38% and stabilized power output. However, the VA-inspired platform exhibited slightly lower buoyancy and draft, which may limit its adaptability to varying water depths.

Recent innovations have increasingly focused on integrating wave energy converters (WECs) to enhance energy harvesting capabilities and vibration control in FOWT platforms. Zhou et al. [19] proposed a semi-sub floating platform (Fig. 4(c)) equipped with oscillating water column (OWC) WECs, which reduced heave, roll, and pitch motions by 35%, 55.4%, and 13.8%, respectively, while optimizing chamber air orifice size for improved efficiency. Building upon this concept, Huang et al. [20] introduced a semi-sub platform with internally installed self-reacting WECs (Fig. 4(d)), which provided superior vibration control across a broader frequency range while increasing energy harvesting potential. These advancements emphasize the growing role of wave energy integration in optimizing floating platform performance.

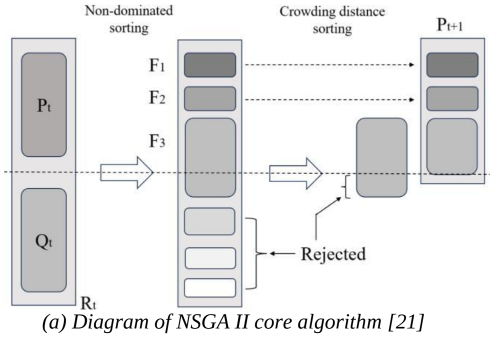
The development of FOWT platforms has progressed from early spar-type designs to hybrid and nature-inspired structures, incorporating fully submersible platforms and wave energy converters to enhance stability, energy efficiency, and resilience. Despite these advancements, challenges remain in construction complexity, material costs, and long-term durability. As offshore wind energy continues to expand, future research will focus on cost-effective and stable FOWT platforms to support large-scale deployment.

3. Novel optimization methods for floating platform

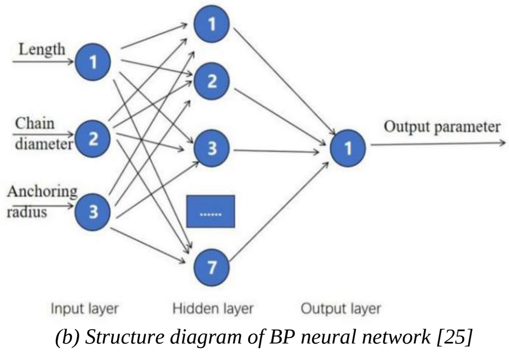
Although various FOWT platforms have been designed, the development of efficient FOWT platforms remains a key research focus. In recent years, substantial research has been dedicated to the design methodologies and theoretical frameworks FOWT platforms, leading to the emergence of numerous optimization techniques aimed at enhancing platform stability, hydrodynamic performance, and cost-effectiveness. This section categorizes these optimization methods into two primary approaches: evolutionary and genetic algorithm-based optimization, and structural and analytical optimization techniques.

3.1 Evolutionary and Genetic Algorithm-Based Optimization

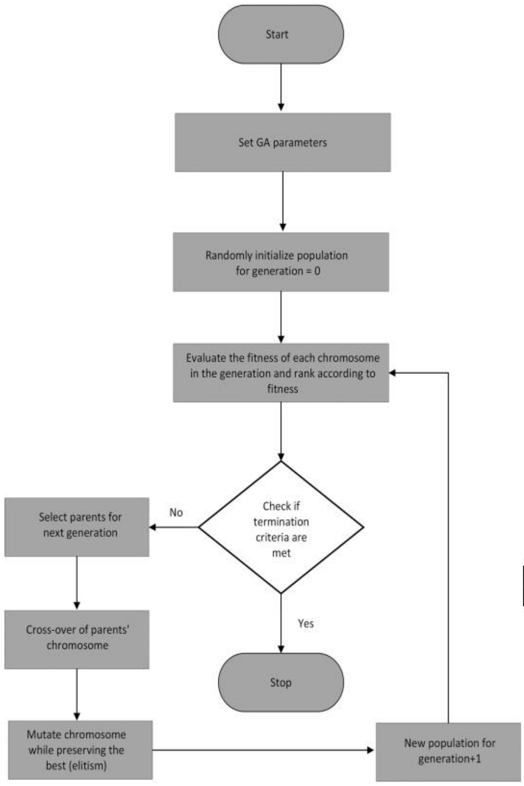
Genetic algorithms (GAs) and evolutionary methods are among the most widely used approaches in platform design optimization. These techniques explore large parameter spaces to identify optimal configurations that enhance platform stability, hydrodynamics, and cost efficiency. Pan et al. [21] applied a multi-objective genetic algorithm (Fig. 5(a)) to optimize a semi-submersible FOWT platform, focusing on mass reduction and hydrodynamic efficiency. Their study revealed significant improvements in resonance characteristics and emphasized the importance of mooring system redundancy under extreme conditions. Similarly, Giulio et al. [22] utilized a GA-based approach (Fig. 5(c)) to optimize the dimensions of a 10 MW semi-sub platform, yielding a more compact and efficient design compared to the direct scaling of a 5 MW platform.



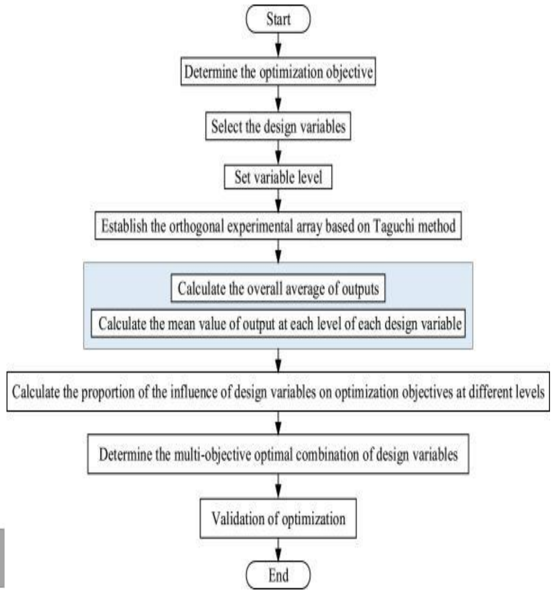
(a) Diagram of NSGA II core algorithm [21]



(b) Structure diagram of BP neural network [25]



(c) The genetic algorithm process flow chart [23]



(d) Multi-objective optimization process based on the Taguchi method [27]

Fig. 5 Algorithm and frame structure diagram

Further advancements in GA-based optimization were demonstrated by Alberto et al. [24], who introduced the Hexafloat platform. Their findings indicated that a structurally optimized, smaller platform could outperform conventional spar-buoy and semi-sub designs, reducing material costs while maintaining stability. Additionally, Jiang et al. [25] integrated neural network (Fig. 5(b)) models with genetic algorithms to optimize mooring system parameters for a 10 MW turbine, effectively balancing cost and safety. These developments have significantly refined platform designs while minimizing computational effort.

3.2 Structural and Analytical Optimization Methods

Beyond evolutionary algorithms, structural and analytical approaches have emerged as crucial techniques for optimizing floating platforms. These methods focus on material efficiency, structural refinement, and reliability, addressing challenges such as stress distribution, multi-variable interactions, and uncertainty management.

Topology optimization methods have played a key role in refining platform designs. Saeed et al. [26] introduced a density-based topology optimization approach to develop a lightweight, multifunctional platform integrating wind, solar, and wave energy systems. Their method reduced total mass by 40.82% while enhancing stiffness and durability. Similarly, Ren et al. [27] employed an orthogonal test method to optimize local platform structures, achieving a 22.12% reduction in maximum stress without altering mass or centroid properties. Despite their effectiveness, these methods face computational complexity and scalability challenges when applied to large-scale systems.

Moreover, several advanced optimization methods have been proposed and applied in recent years. Xie et al. [28] utilized the Taguchi experiment method (Fig. 5(d)) to optimize a semi-sub platform, achieving a 26% increase in platform mass (excluding ballast) while surpassing the OC4 reference model in dynamic responses. Roach et al. [29] and Jeffrey et al. [30] developed generalized upscaling methodologies for semi-sub platforms, facilitating the transition from 5 MW to 30 MW wind turbines. Their research highlighted critical trade-offs: increasing column radii raises mass and heave periods, whereas adjusting column distances affects metacentric height.

The evolution of floating platform optimization methods has progressed from traditional genetic algorithm-based approaches to more advanced structural and analytical optimization. Early studies focused on iterative genetic algorithms to refine platform dimensions and mooring configurations, whereas more recent researches demonstrates that structural and analytical optimization methods have led to more efficient and reliable platform configurations, effectively balancing structural integrity, cost, and performance. These advancements contribute significantly to the continuous refinement of FOWT platforms, providing a solid foundation for future large-scale deployment.

4. Attitude Control and Stability Adjustment of Floating Platforms

FOWTs face considerable challenges in maintaining platform stability and optimizing energy production due to their susceptibility to wind-wave disturbances and environmental variability. To address these challenges, researchers have investigated various control strategies aimed at enhancing stability, mitigate excessive platform motion, and improve power efficiency. This section provides an overview of recent advancements in platform attitude control and stability regulation, categorizing the discussion into two primary areas: Active and Semi-Active Control Strategies, Model Predictive and Data-Driven Control Approaches.

4.1 Active and Semi-Active Control Strategies for Platform Stability

Early studies on FOWT platforms primarily relied on passive damping techniques to mitigate platform motion. However, these methods often lacked adaptability to changing environmental conditions. To overcome these limitations, researchers have developed active and semi-active control strategies to enhance platform stability. Zhao et al. [31] introduced a multi-objective optimal control strategy that actively adjusts actuator control amplitudes within predefined limits, effectively balancing control action and mechanical stress. This method extends the operational lifespan of FOWTs while enhancing platform stability.

Yu et al. [32] proposed a semi-active structural control approach utilizing an optimal declutching framework to dynamically adjust the damping coefficients of the power take-off (PTO) system. Their findings indicate that this method significantly reduces platform motion while maintaining flexibility, making it suitable for multi-body floating structures. However, semi-active control strategies still face challenges in balancing energy efficiency with effective damping. Truong et al. [33] conducted a comprehensive review of active control strategies designed to mitigate load fluctuations and improve system stability. Their study highlights the inherent instability of FOWTs caused by wind-wave interactions, material fatigue, and power fluctuations. They emphasize the need to adapt conventional control techniques to address the complex dynamics of floating platforms, which differ significantly from fixed wind turbines.

Xue et al. [34] investigated the hybridization of FOWTs with wave energy converters (WECs) to enhance platform stability. Their control optimization method, based on the CATIFES framework, demonstrated that integrating FOWTs with WECs reduces platform pitch motion and increases overall power output. Despite these advantages, the complexity of coordinating multiple floating bodies presents a significant challenge, necessitating further optimization of control algorithms.

4.2 Model Predictive and Data-Driven Control Approaches

Model predictive control (MPC) has emerged as a powerful technique for minimizing platform motion while maintaining energy efficiency. Ali et al. [35] applied an MPC-based approach to regulate rotor/generator speed and mitigate platform movement. Their findings indicate that MPC outperforms traditional proportional-integral (PI) and linear-quadratic-integral (LQI) controllers, particularly in high-wind conditions. Building on this, Liu et al. [36] refined MPC strategies by incorporating a coupled dynamics model to regulate generator torque and blade pitch. While their approach effectively suppresses platform surge and pitch motion, it introduces fluctuations in power output, highlighting a trade-off between stability and energy consistency.

Zhang et al. [4] developed a data-driven predictive control method that integrates deep learning and multi-objective optimization to improve power regulation and reduce mechanical load on the blade root. However, compared to traditional collective pitch control, data-driven techniques still exhibit limitations in suppressing platform pitch motion. Future research must focus on enhancing prediction accuracy and adaptability to varying sea states.

Tetsuya et al. [37] introduced an advanced MPC framework that incorporates previewed

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environmental disturbances, such as wave height and wind speed, as predictive variables. Their study demonstrates that this approach significantly improves power output stability while mitigating dynamic loads. These findings underscore the importance of integrating real-time environmental forecasting into control strategies to optimize FOWT performance.

As the offshore wind industry its rapid expansion, ongoing research must must prioritize refining control systems to enhance adaptability, efficiency, and real-world applicability. The development of control strategies for FOWTs has advanced significantly, with researchers exploring various active, semi-active, predictive, and data-driven methods. While active and semi-active control approaches have demonstrated effectiveness in reducing platform motion, further refinement is needed to balance stability with energy efficiency. In parallel, MPC and deep learning-based methods provide innovative solutions by anticipating environmental changes and optimizing control responses. However, challenges remain in areas such as multi-body interaction control, environmental adaptation, and experimental validation. Addressing these challenges will be key to maximizing the potential of FOWT energy systems and ensuring their long-term viability in offshore environments.

5. Conclusion

This paper has provided a comprehensive review of the advancements and challenges in floating offshore wind turbine (FOWT) platforms, examining structural innovations, optimization techniques, and stability control strategies. Various platform designs, including spar, barge, semi-submersible, and tension leg platforms, have been explored, along with recent developments in hybrid and nature-inspired structures. Optimization methods such as genetic algorithms and structural analysis have demonstrated significant improvements in platform stability, hydrodynamics, and cost efficiency. Furthermore, advancements in control strategies, including active, semi-active, and predictive approaches, have enhanced platform stability and energy efficiency under dynamic environmental conditions. Despite these achievements, several challenges remain, particularly in material durability, extreme weather resilience, and energy transmission efficiency. Continued innovation in these areas will be key to unlocking the full potential of FOWT technology and supporting the global transition to renewable energy.

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