Hydrodynamic Characteristics of VLFS in Marine Airport Under Typhoon Driving Waves

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Abstract: An analysis is conducted on the hydrodynamic response law of a single module maritime airport, considering the atmospheric variables of the wind and wave field. The analysis is based on hydroelastic theory and focuses on the typhoon-driven very large floating structures (VLFS) configuration of the maritime airport. The findings indicate that the proposed method enables efficient information exchange between the fluid and structure domains through the coupling interface. The displacement of the maritime airport affected by the typhoon's wave field is mostly determined by the direction of the flow. The wave loads acting on the floating body also influence the wave profile of the irregular wave and the deformation of the floating body. The von Mises stress distribution is not significant in all parts of the floating body.

Key words: typhoon; wave field; maritime airport; hydrodynamic; very large floating structures (VLFS)

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0 Introduction

Approximately 71% of the Earth's surface consists of water. Propelled by the pressing issues of climate change and growing population, there has been a significant surge in the development of floating technologies in recent decades. Very large floating structures (VLFS) have gained significant popularity as they provide support for marine airports, offering a range of functions including aircraft take-off/landing, maintenance, and refueling. This has made them a preferred choice over traditional land reclamation methods. These advantages include minimal environmental impact, the ability to choose from a wide range of locations, and the flexibility to expand or remove the structures as needed[1].

Maritime airport VLFS, extending over several kilometers, are essential for marine economic development and security. They necessitate structural flexibility to manage the nonlinear dynamic responses induced by typhoons and waves, such as elastic deformation and fluid-solid coupling, which poses challenges to current engineering standards[2-4].

When it comes to the dynamic response characteristics of VLFS, the most commonly used method is the rigid module flexible connection (RMFC) method[5-6]. Karmakar et al.[7] examined the interaction between waves and multiple articulated platforms by dividing the offshore super large floating platform into separate modules. Meanwhile, Gao et al.[8] demonstrated that the hydroelastic response of VLFS could be effectively reduced through RMFC connection.

Previous research utilizing RMFC or continuous beam modeling has concentrated on floating structures subjected to regular waves. However,

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there is still little understanding of how maritime airports respond to irregular waves. The substantial elastic response of water in current-wave environments, combined with single modules measuring approximately 300 m in length, requires the exploration of alternative modeling approaches. This investigation examines the hydrodynamic response of a single module through the application of a novel flexible module rigid connection (FMRC) method, simulating the performance of very large floating structures under extreme waves induced by typhoons using STAR-CCM+ software. This study utilizes the hydroelastic theory to analyze stress, displacement, and fluid forces, providing essential insights for the design of maritime airports.

1 Modeling and Simulation

1.1 Multi-flexible rigid hybrid modeling method

This paper explores the development of a single module highly large floating structure with the goal of designing a maritime airport.

The deformation of the floating body must adhere to the slope specifications of airport pavement in China. In contrast to the traditional RMFC model, the maritime airport's single module is designed using stronger steel. Additionally, a novel connection method called multiple flexible module rigid connection (FMRC) is employed to consider the module's deformation. Moreover, the design employs a flexible module rigid connection method to ensure stability under dynamic wave loads, with flexible modules distributing stresses and rigid connections preserving integrity, suitable for the high-energy wave spectra associated with Typhoon Megi[9-12]. This approach improves adaptability, contrasting with the traditional offshore designs that emphasize stability through the use of stiff modules and flexible connections in a rigid module flexible connection method[9-11]. Each individual module contains an upper floating plate. The structure consists of five lower floating plates, ten columns, and eight bracing rods. The design parameters of a single module are presented in Table 1[13].

Table 1　Main design parameters of single module

Parameter	Value	Parameter	Value
Total length/m	300	Density/(kg·m^{-3})	7 850
Total width/m	100	Young's modulus/Pa	2.10×10^{11}
Total height/m	27	Poisson coefficient	0.30
Underwater height/m	14	Roll inertia moment	2.11×10^{12}
Column height/m	16	Pitch inertia moment	1.73×10^{13}
Column diameter/m	18	Yaw inertia moment	1.90×10^{13}
Drainage volume/m^3	854 219.44	Displacement/t	85 213

VLFS of the maritime airport is deployed in the South China Sea. It is composed of a semi-submersible single module floating body structure with a total length of about 300 m. The adjacent of the module is connected laterally by two connectors through fixed hinge coupling, and the module motion rules adopt the free motion mode. The multi-flexible rigid model of VLFS of maritime airport is shown in Fig.1.

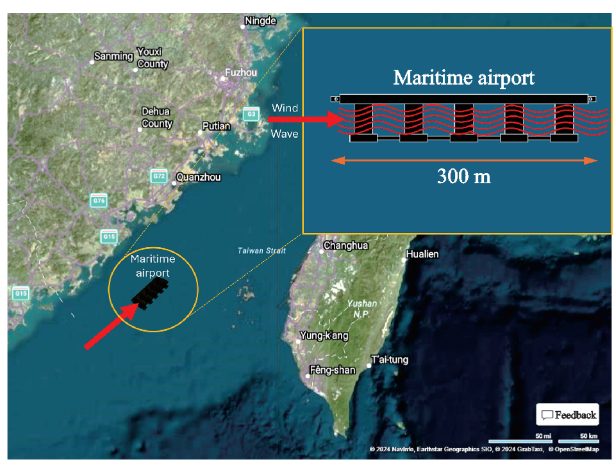

Fig.1　Schematic representation of maritime airport at the South China Sea under the typhoon wave field

Based on the wave spectrum data collected during Typhoon Megi, the Jonswap spectrum parameters have been determined by considering the width of the wave spectrum. Based on the correlation between the wave spectrum width and the peak lifting factor[13], it is determined that the peak lifting factor in the Jonswap spectrum is 5.6 and the effective wave height is 5.2 m.

Since it captures sharp spectral peaks, the Jonswap spectrum is useful for assessing tropical cyclone-influenced developing seas[14]. The chosen $\gamma = 5.6$ reflects the powerful wind and narrow-banded wave energy during typhoons, consistent with comparable extreme events[15]. Using regional wave hindcast data for Typhoon Megi (e. g., WAVEWATCH Ⅲ), a substantial spectral peak supports a higher γ value within the typical range of 3—7 for tropical storms[16]. This conclusion is congruent with empirical findings of storm-driven seas in the study area, ensuring an accurate wave field representation. The Jonswap spectral parameters, which represent extreme wave conditions, are used as boundary conditions for the calculation domain of the small-scale typhoon wave field.

1.2 Computing domain and meshing

The numerical study simulates the hydroelastic response of a maritime airport under typhoon waves. Fig.2 shows the numerical pool's domain size for a 300 m long single module, with the total airport length at $8L$. To minimize wave reflection errors, the domain is set to $12L$ (flow direction), $2L$ (cross direction), and $0.4L$ (vertical direction). Wind waves are generated based on wave spectrum parameters, with a maximum wind speed of 52 m/s at 10 m height and a stable seawater velocity of 2 m/s, ignoring minor horizontal velocity changes.

Fig.2 shows the boundary conditions utilized in the modeling approach, a pressure outlet located at the outer boundary, symmetrical planes positioned at the sides of the structure, and velocity inlets at the other four planes to define the wave velocity and to reduce wall-flow gradients. The volume of fluid method monitors the air-water interface, whereas the fluid-structure interaction model addresses the interactions between fluid and structure, enabling reciprocal effects on deformation and forces.

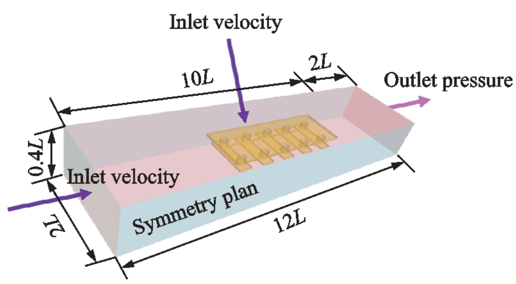

Fig.2 Single module VLFS and its boundary conditions

Fig.3 illustrates the organized grid of the computational domain, employing dynamic mesh technology to model structural rotation, translation, and deformation. An encrypted grid area surrounding the maritime airport enhances displacement calculations, utilizing regionally optimized grid density to ensure precise capture of seawater flow and structural deformation.

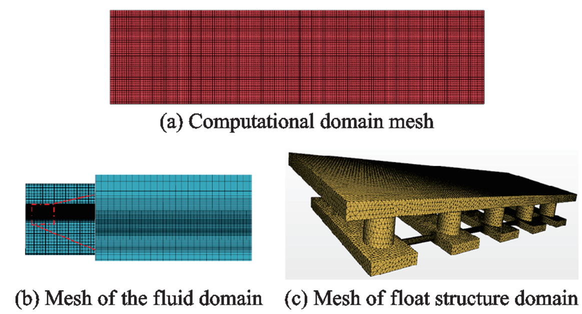

Fig.3 Computing domain structured grid

2 Results

2.1 Wave surface elevation of flow field

Fig.4 displays the wave surface elevation of the entire interaction between the fluid and solid interface at a specific moment. Examining the flow field intricacies, such as the floating body's water entry

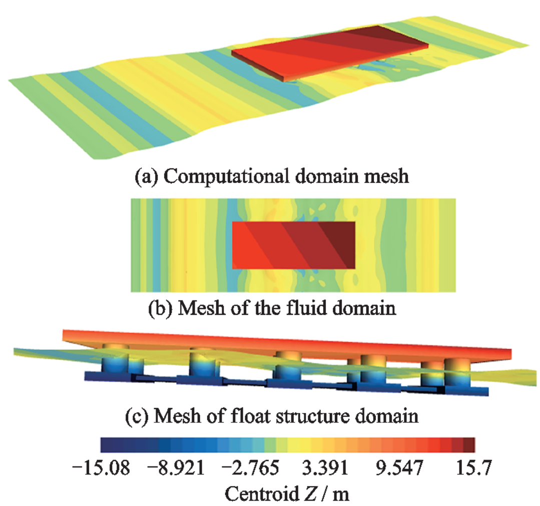

Fig.4 Wave profile

and exit, its elastic deformation, and any disturbances to the free surface. Fig.4 clearly illustrates the non-periodic pattern of wave loads on the floating body.

During the wave propagation process, the wave heights gradually decrease when they contact with the VLFS body due to factors like fluid viscosity and numerical dissipation in the computation.

2. 2 Displacement

The extent of the change of the displacement that occurrs at the marine airport at various times is shown in Fig.5. The displacement represents the change in position of the maritime airport along the three coordinate axes in comparison to its original position with respect to the coordinate system. Fig.5 demonstrates that VLFS moves in all directions whenever the fluid touches with it.

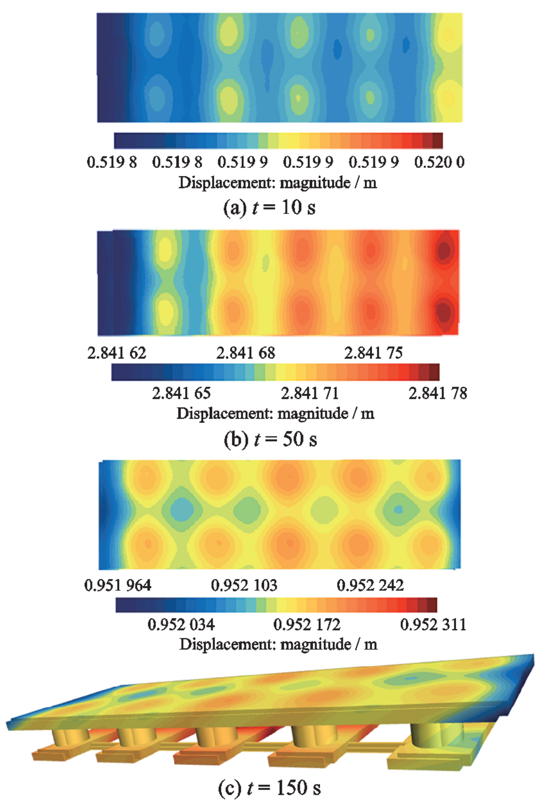

Fig.5 Displacement distributions of the VLFS body over time

This case suggests that the deformation that occurs in all directions as a consequence of the waves acting on the floating body of the maritime airport has an effect on the displacement of the body. In addition, it is possible to observe that the VLFS body displacement is eliminated when the duration of the wave is taken into consideration.

2. 3 Von Mises stress

Fig.6 illustrates the distribution of von Mises stress over time for a single VLFS module subjected to the wave conditions of Typhoon Megi. The analysis reveals minimal stress levels, which can be linked to the design of the flexible module rigid connection. This design effectively dissipates wave-induced forces through deformation, consistent with the anticipated performance of structures resistant to typhoons[9]. This validates the design's safety and durability, with conservative margins that guarantee integrity in the face of high-energy waves, aligning with offshore standards[12]. An observable increase in stress is noted at the contact points where bracing rods meet the lower floating plates.

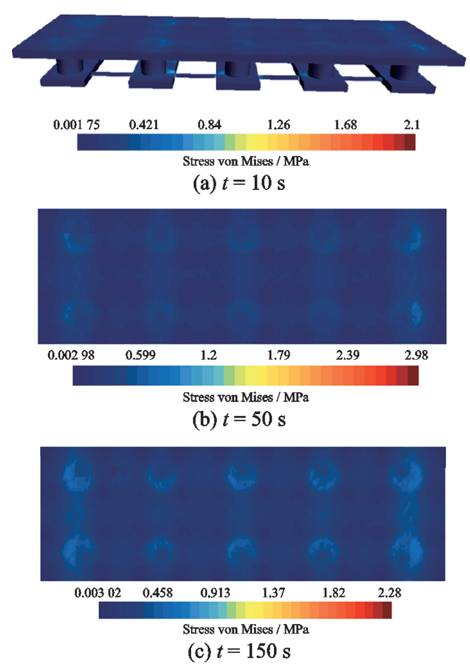

Fig.6 Von Mises stress distributions over time

3 Conclusions

This paper analyzes the impact of environmental factors, such as wind and waves, on VLFS. It investigates the distribution of stress, displacement, and fluid forces using hydroelastic theory. Here are the main conclusions.

(1) The proposed method enables efficient information exchange between the fluid and structure domains through the coupling interface. The numerical results of the elastic deformation of the floating body are satisfactory.

(2) The wave loads acting on the floating body also influence the wave profile of the irregular wave and the deformation of the floating body.

(3) The displacement of a maritime airport during a typhoon wave field is caused by the movement of the floating body in various directions.

(4) The highest von Mises stress of the single module is found at the brace and the connection between the lower floating plate and the brace.

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Author contributions Mr. **HILÁRIO Gerson** conducted the writing of the original draft, design methodology, and data curation. Prof. **KE Shitang** contributed to concept of the study, review and funding acquisition. Dr. **LI Wenjie** and Dr. **HILÁRIO Jonas** contributed to supervision, review and edited the manuscript. All authors commented on the manuscript draft and approved the submission.

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台风驱浪作用下海上机场超大浮体水动力特性

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摘要: 考虑风场和波浪场气象变量变化,对单模块海上机场的水动力响应规律进行了分析。基于流固耦合理论,重点研究了台风影响下的海上机场超大浮体结构。研究结果表明,所提出的方法通过耦合界面能够在流体和结构域之间实现高效的信息交换;台风、波浪场作用下海上机场的位移响应主要受波浪流向控制,作用在浮体上的波浪载荷也会影响不规则波的波形以及浮体的变形情况;浮体所有部位von Mises应力分布并不显著。

关键词: 台风;波浪场;海上机场;水动力特性;超大浮体