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Research Status on the Structural Optimization of Offshore Crane Vessel Foundations

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Abstract

With the growing demand for marine resource development, offshore crane vessels, as key equipment in marine engineering, are becoming larger with enhanced lifting capacities. Consequently, the loads borne by the crane vessel foundations have increased, posing higher requirements for structural safety and lightweight design. Conducting structural optimization research on the foundations is crucial for improving load-bearing capacity, reducing weight, and lowering costs. This paper reviews the current state of research on crane vessel foundation structures. Scholars both domestically and internationally have conducted extensive studies on the strength of crane vessel foundations, focusing primarily on three aspects: material research, structural design optimization, and advancements in manufacturing processes. Studies show that the application of new materials, such as high-strength steel and composites, has improved the strength and stiffness of the foundations. Methods like finite element analysis and topology optimization have refined the structural design, enhancing load-bearing capacity and fatigue resistance. Furthermore, advanced manufacturing techniques, such as robotic welding and 3D printing, have increased the precision and quality of foundation fabrication. Based on the current research status of crane vessel foundations, two major future research trends are proposed: First, in terms of structural strength analysis, more refined models and efficient computational methods should be adopted to enhance the optimization of foundation performance. The shift from traditional ship beam theory to modern finite element analysis will improve simulation accuracy and structural strength. The focus should also be on changes in vessel size and working environment to meet more complex demands. Second, attention should be given to nonlinear and dynamic responses, considering the effects of large deformations and nonlinear behavior during actual operations. This includes addressing complex loading scenarios, such as the motion of lifted objects and wind forces, to ensure the strength and stability of the foundation.

Keywords

Offshore Crane Vessel; Crane Base; Structural Strength Analysis; Structural Optimization Design.

1. Introduction

With the increasing depletion of land resources and the growing global demand for energy, countries are increasingly turning their attention to the ocean as a new frontier for strategic resources. The high-tech applications in marine engineering have also led to a gradual reduction in resource development costs. Against this backdrop, large offshore crane vessels have rapidly developed as key equipment in marine engineering.

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The Thialf crane vessel, owned by Heerema Group from the Netherlands, is currently the largest semi-submersible crane vessel in the world, built in 1985. It is equipped with two large rotary cranes, capable of lifting 14,200 tons with dual hoists. The Thialf has an overall length of 201.6 meters, a width of 88.4 meters, a depth of 49.5 meters, and a maximum draft of 31.6 meters.

The Saipem 7000 crane vessel from Italy's Saipem company is equipped with two rotary cranes, each with a capacity of 7,000 tons, giving it a total lifting capacity of 14,000 tons. The Saipem 7000 has provided support for offshore projects in various countries around the world. It has an overall length of 197.95 meters, a width of 87 meters, a depth of 43.5 meters, and a maximum draft of 27.5 meters.

Figure 1. Thialf Semi-submersible Crane Vessel

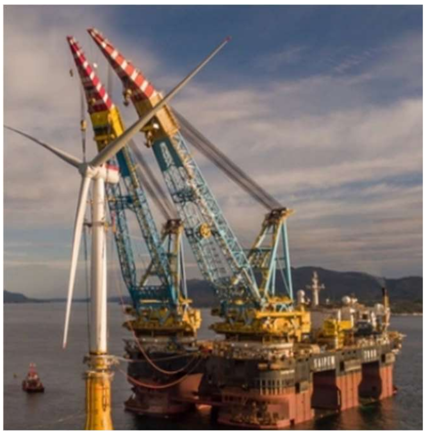

Figure 2. Saipem 7000 Semi-submersible Crane Vessel

Here is an introduction to some of the most representative crane vessels in China:

The "Lanjing" large crane and pipelaying vessel is a non-self-propelled, unlimited range operation engineering ship. It has an overall length of 157.5 meters, a width of 48 meters, and a full-load displacement of 58,000 tons. The vessel is capable of performing lifting and pipelaying operations in water depths of up to 150 meters. It is equipped with a 3,800-ton full-rotary crane and has a pipelaying system on board with both single-pipe and double-pipe laying modes, as well as a helicopter platform.

The "Tianyi" 3,000-ton transport and lifting vessel is a crane vessel designed, invested in, and built by China Railway Bridge Bureau to advance bridge construction projects. It is used for the transportation and installation of bridge structures for the Hangzhou Bay Bridge, aiming to bring China’s bridge construction into the ranks of global leaders and enhance the company’s core competitiveness globally. The "Tianyi" has an overall length of 88.2 meters, a width of 40 meters, a depth of 7 meters, and an operational draft of 4 meters.

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Figure 3. “Lan Jiang”Pipe Laying Crane

Figure 4. “Tian Yi”Transport Girder Crane

In the field of marine engineering, the design of crane vessel foundations faces significant challenges due to the complex effects of wind and waves. These challenges are crucial for ensuring the safe operation of the foundation structures under harsh weather conditions. To address these challenges, researchers are actively developing innovative design and optimization strategies aimed at enhancing the performance and stability of these foundations. During actual operations, crane foundations must not only support operational loads but also withstand environmental loads, which can lead to potential safety risks such as fatigue cracks. Therefore, conducting fatigue analysis of crane foundations is a key step in ensuring safety in marine operations.

Research on the optimization of crane vessel foundation structures has attracted considerable attention. Early studies primarily focused on the development of theoretical models. With advancements in computer technology and numerical simulation methods, researchers have begun to use more complex numerical simulation techniques, such as finite element analysis, to more accurately simulate marine environments and assess the performance of foundation structures.

The goal of structural optimization design is to meet specific operational requirements or multiple standards through continuous improvement to achieve optimal structural performance. Although there have been some successful cases of foundation structure optimization, current research still faces a series of challenges, such as limited understanding of multi-factor coupling, underexplored applications of new materials, and the need for more in-depth research on comprehensive optimization strategies.

Therefore, future research needs to strengthen multi-faceted considerations in foundation structure optimization to more comprehensively and deeply address complex issues in practical engineering. A comprehensive review of the current status and development trends in crane vessel foundation structure optimization research is needed. This should include an in-depth exploration of the application of different optimization methods, the interrelationship between numerical simulations and experimental research, an evaluation of the strengths and weaknesses of current research, and the identification of key issues and development directions for future research. Such a review will provide researchers in the field of crane vessel foundation optimization with a thorough reference and promote further development in this area.

1.1 Current Research on the Structural Strength of Crane Vessel Foundations

Research on the structural strength of ship hulls has a long history both domestically and internationally. Early studies primarily relied on traditional methods based on beam theory, treating the ship as a hollow beam structure for approximation purposes. However, this approximation method had limitations, as its accuracy was suitable only for slender and regular ship shapes. For irregular hull shapes, especially those with complex structures, the calculation accuracy was insufficient. With the development of modern finite element technology, structural strength analysis for large and complex vessels has become feasible through finite element methods, greatly facilitating the design and calculation process.

Finite element analysis simplifies complex problems for solution calculations. Specifically, the method treats the computational domain as many interconnected finite element subdomains, then assumes each subdomain has an approximate solution and derives the conditions for the entire domain to obtain the final solution to the problem.

This method can handle irregular shapes and special boundary conditions more accurately, allowing a better representation of the actual stress conditions on the hull. This significant advantage has led to the widespread adoption of finite element methods by researchers.

In his paper, Feng Kang proposed a theoretical framework based on the variational principle and difference format. Between 2014 and 2019, multiple studies focused on the strength analysis of crane foundations and hull structures. For instance, Wang Wei and colleagues used MSC.Patran/Nastran software for modeling calculations and confirmed that the local strength of crane foundations met design specifications. In 2015, Xu Fanfan and others conducted a static strength analysis of a 12,000-ton crane vessel's foundation, highlighting issues that need attention in related designs. In 2016, Xiao Hui and colleagues used the same software to establish a finite element model for an 800-ton crane foundation and hull support structure, finding that the structural strength met requirements and proving the feasibility of this method for verifying large rotary crane support structures. In 2017, Zhang Jian and colleagues analyzed the structural strength of a 100-ton non-self-propelled offshore transfer platform using direct calculation methods, identifying high-stress areas and local strength patterns in crane foundations and other components, and proposed strengthening solutions. Finally, in 2019, Bi Yuewen and colleagues studied the crane foundation of a bulk carrier, using finite element software to establish a model and verify that the crane's strength complied with design standards.

In terms of simulation research on crane vessel foundations, the current research status can be summarized as follows: finite element analysis methods have become mainstream. By decomposing complex foundation structures into finite element subunits, their interconnections allow for more precise simulation of foundation behavior under various load conditions.

1.2 Current Research on the Fatigue Strength of Crane Vessel Foundations

The study of fatigue problems has a history of over a hundred years. The concepts of fatigue limit and S-N curves were first introduced by scholars in 1847, laying the theoretical foundation for fatigue strength research. Subsequently, in 1910, Basquin described the laws of metal S-N curves, and in 1945, Miner proposed the fatigue linear cumulative damage theory. In 1963, Paris introduced the power-law equation for fatigue crack growth rates, which was revised by Forman in 1967. Fatigue failure has become one of the main modes of failure in marine structures, drawing widespread attention from experts in the fields of shipbuilding and marine engineering, and leading to continuous improvement of relevant design codes.

Mechanical structures, such as crane foundations on crane vessels, often suffer from fatigue failure, which directly affects the operational lifespan of the crane vessels. In 2013, Xu Yingnan and colleagues investigated the fatigue issues of crane foundations in a large VLCC retrofit project. They

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used Abaqus software to obtain stress amplitudes at various fatigue hotspot locations and applied DNV fatigue calculation formulas to assess fatigue under different stress states, outlining basic methods for calculating fatigue damage in crane foundations. In 2015, M. Fonte and others assessed the integrity of container ship crane foundations and columns after structural damage. The results indicated that during cargo handling, compartments, foundations, and columns are subjected to varying degrees of overload, fatigue, and corrosion from harsh marine environments. Also in 2015, Zhang Yanchang and colleagues studied the fatigue damage of a crane foundation on an FPSO. They combined deterministic methods with spectral analysis methods for structural fatigue analysis, completed yield and fatigue strength checks for the crane foundation, and performed optimization design and analysis of the foundation structure. In 2017, Cui Jin and others analyzed the fatigue damage of a 20-ton deck crane foundation on a semi-submersible drilling platform in the North Sea of China. They systematically summarized fatigue analysis methods based on fatigue damage, using work load and environmental acceleration with various cycle distributions as input variables. They calculated fatigue damage from environmental loads and work loads using simplified fatigue algorithms and S-N curve methods, ultimately determining the total fatigue damage of the foundation as a basis for evaluating whether the foundation's fatigue strength meets standards. In 2020, Chen Wenke and colleagues studied the crane foundation of a 2,200-ton semi-submersible lifting and dismantling platform, calculating the combined fatigue damage of the foundation under wave loads and working loads. Their analysis revealed that most fatigue damage at hotspot locations was primarily caused by the crane's working load, while a few hotspots had significant fatigue damage from wave loads due to the arrangement of the hull structure.

Currently, fatigue calculations for crane vessel foundations mainly use S-N curves and cumulative damage principles, considering the effects of crane working loads and environmental wave loads on fatigue damage. Research on crane vessel foundation optimization has become a hot topic among scholars domestically and internationally. In recent years, researchers have utilized advanced finite element analysis techniques and optimization algorithms to explore the effects of various structural parameter changes on foundation strength and stability, aiming to improve performance and reduce structural loads.

Current Research on Structural Optimization Design of Crane Vessel Foundations

Initially, ship structural optimization used numerical optimization methods. With the advancement of modern computer technology, finite element analysis, and mathematical modeling, contemporary intelligent optimization algorithms have become widely applied, providing better solutions for structural optimization design problems. Researchers such as N. Hisashi, T. Okada, and Z. Sekulski, along with other international scholars, have studied the issue of lightweight ship structures and applied genetic algorithms to optimize parameters such as rib spacing, dimensions, and plate thickness. In the mid-1960s, Moe and others first proposed using mathematical programming to optimize the deck of automotive transport ships, laying the theoretical foundation for ship structural optimization design. Among various methods, the application of genetic algorithms in ship structural optimization is the most prevalent.

Researchers have conducted studies on direct algorithms as follows: In 2005, Li Zhongwei and colleagues used finite element analysis methods with weight as the objective function and allowable stress as structural constraints. They employed finite element software such as Altair, Isight, and Nastran for optimizing the structure of catamarans, ensuring the hull structure's quality was minimized and did not exceed allowable stress limits. In 2008, Zhang Li and others selected a Panamax container ship for their study, using Patran and Nastran finite element software to establish and analyze models. By calling analysis results through Isight software and using constraints such as plate thickness and allowable stress, they conducted structural optimization design with the total weight of the cargo hold as the objective function. In 2010, Pan Binbin and colleagues used Ansys to establish an analysis model for a ship and performed structural optimization design based on finite element analysis results, targeting hull weight as the objective function and using aggregate size and plate thickness as design variables. They employed Isight software to call structural response results, ultimately reducing the hull weight by approximately 15.57%, with constraint stress not exceeding the original design's stress values. Direct calculation methods, which involve directly calling finite element software for model calculations, result in large computation volumes and low efficiency, leading to the emergence of surrogate model-based optimization methods.

Significant progress has been made in surrogate model-based ship optimization research in China. Zhen Chunbo and others optimized an oil tanker's compartment surrogate model constructed with a BP neural network using particle swarm algorithms, successfully reducing the compartment weight by 0.4%. He Ruifeng and others applied a dual-population genetic particle swarm algorithm to optimize the mid-section of a Yangtze River multi-purpose vessel, achieving a 6.7% reduction in cargo hold weight. Meng Song and others used an improved particle swarm algorithm to optimize the plate thickness of a 107,600 DWT oil tanker, successfully reducing compartment weight by 6.75%. Liu Gang and others combined simulated annealing algorithms and genetic algorithms to improve the collision resistance of FPSO side structures by 21.7%. Kang Caijie and others optimized the weight of a catamaran, achieving an ideal weight reduction effect.

In ship optimization research, genetic algorithms have also made significant advancements. D. Kavlie first applied mathematical programming methods to the optimization design of automotive transport ship decks. C.D. Jang and others performed multi-objective structural optimization on the mid-section of oil tankers, effectively reducing production costs and overall weight. W. Annicchiarico conducted finite element modeling and analysis on a ship and performed structural optimization with satisfactory results. Wu Jianguo and others were the first in China to apply genetic algorithms for ship structural optimization. Guo Xiaodong and others optimized the mid-section of large oil tankers, reducing the hull compartment's mass by 5.2%.

2. Evaluation

Structural optimization of foundations is a complex process involving multiple factors, including but not limited to structural design, material selection, and manufacturing processes. Throughout history, researchers have proposed and implemented various methods for optimizing foundation structures, such as numerical simulations, finite element analysis, and genetic algorithms. These methods have achieved significant results in enhancing foundation performance; however, each has its own limitations. Therefore, there is a need for continuous exploration of new methods and technologies to achieve greater breakthroughs in the field of foundation structure optimization.

Firstly, most existing optimization methods are based on deterministic models, which means they typically assume that all input parameters are known and constant during the optimization process. However, in practical applications, many parameters (such as material properties and loading conditions) may exhibit some degree of uncertainty. Therefore, optimization methods need to account for these uncertainties to obtain more reliable results. This requires that the design and implementation of optimization strategies must fully consider and address these uncertainties to ensure the reliability and effectiveness of the optimization results.

Secondly, many optimization methods require substantial computational resources. For example, finite element analysis and numerical simulations often need a significant amount of computation time, especially for complex foundation structures or high-precision simulations. This limits the application of these methods in large-scale or real-time optimization problems. Therefore, there is a need to find an optimization method that can ensure effective results while efficiently utilizing computational resources to meet the demands of large-scale or real-time optimization.

Additionally, most existing optimization methods focus on a single optimization objective, such as minimizing weight or maximizing stiffness. However, in practical applications, it is often necessary to consider multiple optimization objectives simultaneously, such as weight, stiffness, and durability. This necessitates the development of methods capable of handling multi-objective optimization problems. Therefore, there is a need to find an optimization method that can meet multi-objective

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requirements while effectively utilizing computational resources to address practical application needs.

In summary, foundation structure optimization is a complex and important issue. Although many methods have been proposed for optimization, there are still unresolved challenges and problems. Future research needs to continue exploring to find more effective and reliable optimization methods.

3. Development Trends and Outlook

In the field of crane vessel foundation structural optimization, future development trends and prospects will be explored from multiple aspects. By deeply analyzing current research trends, it is possible to better anticipate potential future directions and assess the impact of new technologies and methods on the optimization of crane vessel foundations. This forward-looking perspective not only helps in understanding and addressing future challenges but also provides a framework for identifying and utilizing new opportunities in future research and practice. This will contribute to better meeting the demands of crane vessel foundation structural optimization, thereby enhancing the performance and efficiency of crane vessels.

3.1 Future Development Directions

3.1.1 Intelligent Optimization Technologies

With the rapid development of artificial intelligence and machine learning technologies, future research will place greater emphasis on the application of intelligent optimization technologies. Intelligent algorithms can adapt more flexibly to complex marine environments and enhance optimization outcomes through autonomous learning. Researchers can explore the use of deep learning algorithms to optimize foundation structures, ensuring better performance under various working conditions.

3.1.2 Multidisciplinary Integration Research

Future research will increasingly lean towards multidisciplinary integration, encompassing knowledge from structural engineering, fluid mechanics, materials science, and other fields. By synthesizing research outcomes from various disciplines, a more comprehensive approach to optimizing foundation structures can be achieved, making the research more systematic and thorough.

3.1.3 Adaptation Research for Global Climate Change

As global climate change intensifies, future research will focus more on the adaptability of foundation structures under varying climate conditions. This includes the impact of extreme weather events, such as typhoons and hurricanes, as well as factors like sea-level rise. Researchers will explore ways to enhance the robustness of foundation structures to adapt to the changing climate environment.

3.2 Future Prospects in Research Fields

3.2.1 Green and Sustainable Design

An important future direction in research will be advancing green and sustainable design for foundation structures. This includes the extensive use of environmentally friendly materials, improving energy efficiency, and utilizing renewable energy sources. Through these efforts, foundation structures will better align with the principles of sustainable development and minimize negative environmental impacts.

3.2.2 Multiscale Modeling and Optimization

Future research will place greater emphasis on the development of multiscale modeling and optimization techniques. This means creating more detailed models of foundation structures across different scales, from macro to micro, to more accurately predict their performance. At the same time, optimization strategies will become more refined, taking into account the impacts at various scales.

3.2.3 Performance-Based Design Methods

Future research will increasingly focus on performance-based design methods, which assess and optimize foundation structures based on actual performance metrics rather than solely adhering to traditional design standards. This approach will be more closely aligned with real-world engineering applications, ensuring that designs meet practical needs.

4. Conclusion

Through the literature review on the optimization of ship crane base structures, a series of important points and findings have been derived, emphasizing the existing research achievements and future development trends in this field. This section summarizes the main points of the literature review, highlights contributions to the optimization of ship crane base structures, and discusses the importance of future research.

Principles and Universality: The finite element analysis (FEA) method has become the mainstream technology for studying hull structural strength due to its ability to handle complex structures and load conditions, providing high-precision simulation results. Its universality lies in its broad applicability, whether for regular or irregular hull structures.

Exceptions or Unresolved Issues in Research: Although significant progress has been made in structural strength assessment using FEA, challenges may still exist in simulating hull responses under extreme conditions and the long-term effects of fatigue. Additionally, further improvements in computational efficiency and optimization algorithms remain current research focuses.

Similarities and Differences with Previous Research: In recent years, researchers have utilized advanced software and algorithms, such as MSC.Patran/Nastran and Abaqus, for more in-depth static and fatigue strength analyses of crane bases. Compared to earlier studies based on hull beam theory, modern research focuses more on practical applications and optimization design.

Theoretical and Practical Significance and Value: Through finite element analysis and optimization design, it is possible to significantly improve the safety and economic efficiency of hull structures, reduce structural loads, and extend service life. This has important theoretical and practical significance for shipbuilding and marine engineering.

Recommendations for Further Research: Future research could focus on improving computational efficiency, developing more accurate fatigue analysis models, and exploring new structural optimization algorithms. Additionally, considering the long-term impact of environmental factors on hull structures, such as corrosion and marine environmental changes, is also a valuable direction for further study.

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