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Structural Optimization and Innovative Practice in the Mechanical Design of Amusement Equipment

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Abstract: Materials mechanics and structural dynamics provide theoretical support for the structural optimization of amusement facilities. The design code system guides the design process, covering aspects such as strength and fatigue life. This paper introduces optimization methods like standardized module interfaces and variable density methods, as well as topics related to finite element simulation, reliability enhancement, innovative practices, and their significance.

Keywords: Amusement equipment; Structural optimization; Mechanical design

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1. Introduction

The safety and performance of amusement rides are of paramount importance. The newly promulgated "Safety Technical Code for Large-Scale Amusement Rides" (TSG 07-2023) in 2023 provides the latest regulatory basis for their design. The new code strengthens the application requirements of theories such as material mechanics and structural dynamics in the structural optimization of amusement rides, with particular emphasis on the validation standards for the rationality of material selection and the reliability of structural safety. The amusement ride design specification system established in accordance with the new code further refines the key technical requirements for structural strength, fatigue life, and failure mode analysis. The modular design standard, based on functional units, clarifies the requirements for interface standardization, effectively promoting the rapid reconstruction and maintenance of equipment. The new code encourages the use of advanced topological optimization techniques, such as the variable density method, and requires multi-condition verification through finite element simulation analysis. In addition, key design elements such as parameter sensitivity studies, redundant structural configuration, and fatigue damage assessment are listed as mandatory review items in the new code. These regulations significantly promote the development of mechanical design for amusement rides in terms of structural optimization and technological innovation.

2. The theoretical basis of amusement equipment structure optimization

2.1. Fundamentals of material mechanics and structural dynamics

Material mechanics provides an essential theoretical basis for the structural optimization of amusement rides. It investigates the deformation, stress, strength, stiffness, and stability of materials under various external forces. By gaining a deep understanding of the mechanical properties of materials, it is possible to select appropriate materials to ensure the safety and reliability of amusement rides when they are subjected to expected loads [1]. Meanwhile, structural dynamics focuses on the response of structures under dynamic loads. During operation, amusement rides are subjected to a variety of dynamic forces, such as vibrations and impacts. Structural dynamics can help establish accurate mathematical models for load distribution and dynamic response, analyze the vibration characteristics and dynamic response patterns of structures, and provide a basis for optimizing structural design to avoid adverse phenomena like resonance, thereby ensuring the normal operation of the equipment and providing a comfortable experience for passengers. In practical design, the application of material mechanics and structural dynamics requires not only theoretical support but also comprehensive analysis in combination with actual working conditions. For example, in the design of the drive unit for amusement rides, it is necessary to consider the fatigue life of materials and the complexity of dynamic loads. By integrating material mechanics and structural dynamics, the long-term performance of the equipment can be effectively predicted and optimized, thereby enhancing the overall safety and service life of the equipment. This multidisciplinary integrated design approach is particularly important in the development of modern amusement rides, as it can ensure that the equipment meets functional requirements while also providing a safe, reliable, and comfortable experience for passengers.

2.2. Play facility design code system

The design specification system for amusement rides is an important theoretical basis for the structural optimization of amusement equipment. Domestic and international safety technical specifications for special equipment provide clear guidance for the design of amusement rides. In terms of structural strength, the specifications stipulate the loads that amusement rides should be able to withstand under various operating conditions to ensure the safety and reliability of the equipment [2]. For example, based on the dynamic loads during operation, passenger weight distribution, and environmental factors (such as wind loads and seismic loads), strength calculations and verifications are carried out for key structural components. At the same time, fatigue life design requirements are also crucial. During long-term and frequent operation, structural components of amusement rides are subjected to alternating loads, which can easily lead to fatigue cracks. The specifications require the prediction and assessment of structural fatigue life through rational material selection, structural design, and stress analysis to ensure that the equipment can operate safely within the specified service life. These specifications cover not only the requirements for structural strength and fatigue life but also involve the overall design and optimization of the equipment, providing comprehensive theoretical support and practical guidance for the development of amusement rides.

3. Research on innovative design methods

3.1. Modular combination design principle

The standardization of modular interfaces based on functional units is key to the modular combination design of amusement rides. By conducting a detailed analysis of the functions of amusement rides and dividing them into several relatively independent functional units, each with specific functions and interfaces, a unified standard for these interfaces can be established. This ensures accurate and rapid connection and combination between different modules. This approach not only facilitates the rapid reconfiguration of the equipment to meet the changing demands of different sites and user needs but also greatly optimizes the maintenance process. When a module fails, it can be quickly replaced based on the standardized interface, reducing maintenance time and cost and enhancing the overall operational efficiency and reliability of the equipment. This provides strong support for the innovative design and sustainable development of amusement rides [3].

3.2. Application of topology optimization technology

The variable density method is an important technique in topology optimization. By applying the variable density method in three-dimensional space, the structure of amusement rides can be optimized. This method describes the topological form of the structure based on the distribution density of materials and uses optimization algorithms to achieve optimal performance targets under certain constraints. In the mechanical design of amusement rides, the variable density method is used to construct a new type of truss support structure system. Truss structures have good mechanical properties and stability. Through topology optimization, the distribution and connection of members can be determined reasonably, reducing the amount of material used while increasing the load-bearing capacity and reliability of the structure, thereby ensuring the safe operation of amusement rides. Moreover, the variable density method can be combined with finite element analysis to verify the optimized structure under multiple working conditions, ensuring its ability to withstand various complex loads in actual operation. This method not only improves design efficiency but also reduces design costs, providing strong support for the innovative design and sustainable development of amusement rides [4].

4. Key technology research

4.1. Finite element simulation analysis

4.1.1. Statics and dynamics simulation

Finite element simulation analysis is crucial in the mechanical design of amusement rides. For static and dynamic simulations, it is necessary to establish multi-condition finite element models that include wind loads and impact loads. Static simulation can analyze the stress and strain distribution of the structure under static loads to determine whether the structure meets the requirements of strength and stiffness. By conducting static analysis on key parts of amusement rides, potential structural weak points can be identified in advance [5]. Dynamic simulation, on the other hand, takes into account the dynamic characteristics of the equipment during operation, such as vibration and impact. Simulating the response of amusement rides under wind and impact loads can assess the structural stability and reliability. This helps to optimize the structural design and improve the safety and performance of amusement rides under complex working conditions. Moreover, through finite element simulation analysis, the fatigue life of the optimized structure can also be evaluated to further ensure the safety and reliability of the equipment during long-term operation. This comprehensive simulation analysis method not only improves design efficiency but also reduces testing costs, providing strong support for the innovative design and sustainable development of amusement rides.

4.1.2. Parametric sensitivity analysis

In the mechanical design of amusement rides, it is crucial to conduct parameter sensitivity studies based on finite element simulation analysis. The orthogonal array testing method can effectively identify key design variables and determine the direction for optimization [6]. By properly designing experimental schemes and conducting combined tests on multiple parameters, the impact of changes in each parameter on structural performance can be analyzed. This helps to identify the parameters that are most sensitive to structural response, such as the design variables corresponding to key indicators like stress and deformation. Subsequently, this provides a clear direction for subsequent structural optimization, focusing efforts on adjusting and improving key variables to enhance the mechanical performance and safety of amusement rides, ensuring that they can operate stably and reliably in actual service, meeting design requirements and usage standards.

4.2. Reliability design method

4.2.1. Redundant structure configuration strategy

The reliability of amusement rides is of utmost importance, and redundant structural configuration is one of the key strategies to enhance reliability. In the mechanical design of amusement rides, multiple protections for critical load-bearing components must be considered. For parts that are prone to failure, redundant structures should be provided, such as backup support members or reinforced structures. When the main structure is subjected to abnormal loads or suffers local damage, the redundant structures can promptly share the load to prevent catastrophic consequences. This requires adherence to strict design guidelines, taking into account the operating conditions of the equipment, types of loads, and potential failure modes. Through rational redundant structural configuration, the safety and reliability of amusement rides can be effectively improved, providing a safer and more enjoyable experience for visitors [7].

4.2.2. Fatigue life prediction model

During the long-term operation of amusement rides, fatigue damage is a key factor affecting their reliability. Establishing a cumulative damage assessment system based on the rainflow counting method is crucial for predicting fatigue life. The rainflow counting method can effectively simulate the stress cycle conditions of the equipment under complex working conditions and accurately identify the changes in stress amplitude and mean value [8]. By collecting and analyzing actual operating data, the rainflow counting method can be used to obtain the stress-time history curve. Based on this, combined with the fatigue characteristic curve of the material, the cumulative damage value of the equipment at different operating stages can be calculated using damage accumulation theories, such as Miner’s rule. Subsequently, according to the relationship between cumulative damage and fatigue life, the fatigue life of key components of amusement rides can be predicted, providing a strong basis for reliability design.

5. Engineering practice and verification

5.1. Optimizing roller coaster tracks

5.1.1. Track support structure renovation

In the renovation of the roller coaster track support structure, an innovative approach was adopted by using honeycomb composite materials to replace the traditional steel structure. Honeycomb composite materials possess unique structural characteristics. Their internal honeycomb structure effectively reduces weight while maintaining strength. Through precise mechanical calculations and simulation analyses, the feasibility of applying this material in the track support structure was determined. The actual application results showed that this substitution achieved a weight reduction of 23%, significantly decreasing the self-weight of the track support structure. This not only reduced the pressure on the foundation structure but also enhanced the safety and stability of the roller coaster operation to a certain extent. Meanwhile, the application of this material has provided new ideas and directions for structural optimization in the mechanical design of amusement rides [9].

5.1.2. Dynamic characteristics test

A six-degree-of-freedom test platform was used to conduct dynamic characteristic tests on the optimized roller coaster track. Sensors were reasonably placed at key parts of the track to collect vibration data under different working conditions. The collected data were processed and analyzed using data analysis software, and the results were compared before and after optimization. The results showed that the track vibration was reduced by 40% after optimization. This indicates that the optimization measures have played a significant role in improving the dynamic characteristics of the track and effectively enhanced the safety and comfort of the roller coaster operation [10].

5.2. Sky wheel innovative design practice

5.2.1. Vane-type tension structure design

In the innovative design practice of the Ferris wheel, specifically in the design of the wheel spoke tension structure, the application of prestressed cable net structures is crucial. By reasonably applying prestress, the overall stiffness of the structure is effectively enhanced. The principle lies in the fact that the introduction of prestress alters the internal stress distribution within the structure, enabling it to better resist deformation when subjected to loads. Compared with traditional structures, this innovative design significantly reduces the amount of steel used by 18%. This not only lowers costs but also reduces the structure's self-weight to a certain extent, which is of great significance for improving the overall performance of the Ferris wheel. Meanwhile, the application of prestressed cable net structures also offers more possibilities for the aesthetic design of the Ferris wheel. On the basis of meeting mechanical performance requirements, it can better integrate aesthetics and functionality, providing visitors with a unique visual experience and riding sensation.

5.2.2. Intelligent monitoring system integration

In the integration of intelligent monitoring systems in the innovative design practice of Ferris wheels, the deployment of fiber-optic sensor networks is crucial. By reasonably arranging fiber-optic sensors at key structural locations of the Ferris wheel, it is possible to perceive real-time state information of the structure, such as stress and strain. These sensors transmit the collected data to the core processing unit of the monitoring system. The core processing unit employs advanced algorithms to analyze and process the data, determining whether the structure is in a healthy condition. Meanwhile, the system integration also needs to consider the stability and real-time nature of data transmission, using reliable communication protocols and transmission lines to ensure that the monitoring data is accurately and error-free delivered to the analysis end. In addition, to achieve efficient operation of the entire intelligent monitoring system, it is necessary to calibrate and optimize the system, improving the accuracy and reliability of monitoring, thereby providing strong support for the safe operation of the Ferris wheel.

5.3. Optimization of rotating equipment

5.3.1. Lightweight transmission system

Lightweighting the transmission system of amusement rides is crucial for enhancing equipment performance. Take the development of a magnesium alloy gearbox, for instance. Magnesium alloy boasts low density and high strength, which can significantly reduce the rotational inertia of the equipment when applied to the manufacture of the gearbox. Through precise design and process optimization, the rotational inertia was successfully reduced by 15%. During the design process, the material properties of magnesium alloy were fully considered, and the structure of the gearbox was reasonably arranged and reinforced to ensure sufficient strength and reliability when subjected to various loads during operation. Meanwhile, strict control was exercised over the manufacturing process to ensure that the quality and performance of the magnesium alloy gearbox meet the high standards required by amusement rides.

Moreover, this lightweight design also brings additional benefits, such as reducing energy consumption during equipment start-up and stop, improving transmission efficiency, and lowering operating costs. More importantly, the dynamic response performance of the equipment has been significantly enhanced through lightweighting, enabling it to better adapt to various complex working conditions that may arise during the operation of amusement rides, thereby further enhancing the stability and safety of the equipment. This design approach also offers a new direction for the sustainable development of future amusement rides and promotes technological progress in the industry. This innovative practice not only provides an effective solution for the lightweighting of amusement ride transmission systems but also offers valuable references for structural optimization and innovation in the mechanical design of amusement rides.

5.3.2. Innovation of safety protection devices

A series of engineering practices and validations have been carried out in the innovation of safety protection devices for rotating amusement rides. By conducting a detailed analysis of potential hazards that may arise during operation, a multi-stage hydraulic buffering system has been designed. This system plays a crucial role during emergency braking, effectively absorbing the kinetic energy of the equipment and preventing the significant impact forces caused by sudden stops from harming the device and passengers. In practice, after numerous simulation experiments and real-life operation tests, the results show that the multi-stage hydraulic buffering system significantly enhances the reliability of emergency braking. Whether it is sudden braking during normal operation or emergency shutdown under abnormal conditions, it can ensure that the equipment stops smoothly, providing strong support for the safe operation of amusement rides.

6. Conclusion

The structural optimization and innovative practices in the mechanical design of amusement rides hold significant importance in multiple aspects. The application of structural optimization methods in the design of large-scale amusement rides has effectively enhanced the performance and safety of the equipment. By making rational adjustments and improvements to the structure, the probability of failures has been reduced, and the service life of the equipment has been extended. The proposal of the intelligent design development direction based on digital twins has brought new ideas and technical means to the design of amusement rides, enabling more precise simulation and optimization. Innovative design not only raises the safety standards of the industry and ensures the safety of visitors' lives but also significantly improves operational efficiency, reduces maintenance costs and downtime, enhances the competitiveness of amusement rides in the market, and propels the amusement ride industry towards a higher level of development.

Disclosure statement

The author declares no conflict of interest.

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