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Structural Safety Assessment and Improvement Measures in Mechanical Design of Amusement Equipment

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Abstract: This paper focuses on the mechanical structure design of amusement rides, elucidating the application of fundamental theories such as statics and fatigue strength analysis. It introduces special requirements like impact and alternating stress, explores methods for structural safety assessment and their limitations. The paper also covers principles for selecting indicators, the construction of a grading evaluation system, and the application of various materials and technologies in amusement rides, emphasizing the importance of structural safety and future development directions.

Keywords: Amusement equipment; Mechanical structure design; Structural safety

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1. Introduction

The mechanical structure design and safety assessment of amusement rides are crucial for ensuring their safe operation. The "Safety Technical Code for Large-scale Amusement Rides" (TSG 71-2023), promulgated in 2023, has further strengthened the safety management requirements throughout the entire life cycle of amusement rides, imposing stricter technical regulations on design, manufacturing, installation, and inspection. This code consolidates existing standards and incorporates analyses of typical accident cases, with particular emphasis on safety elements such as structural strength, fatigue life, and redundant design. It also mandates the use of finite element simulation and multi-condition validation to optimize design.

In terms of safety assessment, the new regulations clarify the principles for covering design document appraisal and type testing, and introduce a dynamic management mechanism, such as the daily control, weekly inspection, and monthly scheduling of quality and safety risks, to enhance the scientific and systematic nature of assessments. Moreover, the code now includes new types of amusement rides, such as the "cliff swing," in its regulatory scope, requiring them to pass design appraisal, type testing, and supervisory inspection to ensure structural safety and reliability. Looking ahead, the design and assessment of amusement rides need to further integrate multi-physics coupling analysis, advanced material applications, and intelligent monitoring technologies to meet the evolving demands of the industry.

2. Basic theory of mechanical structure design of amusement equipment

2.1. Basic principles of mechanical structure design

The mechanical structure design of amusement rides needs to be based on a variety of fundamental theories and principles. Static analysis is used to determine the force situation of the structure under static loads to ensure that the structure's strength and stability meet the requirements. Fatigue strength theory, on the other hand, considers the performance of the structure under repeated loading, which is crucial for amusement ride mechanical structures that are frequently used. Dynamic response characteristic analysis helps to understand the vibration and deformation of the structure under dynamic loads, avoiding adverse phenomena such as resonance.

In addition, the selection of the safety factor is a key aspect of the design, which requires a comprehensive consideration of various factors such as material properties, load uncertainty, and manufacturing processes to ensure that the structure can operate safely and reliably under various working conditions. These design principles not only meet the safety standards for amusement rides but are also closely related to the visitor experience. As research has pointed out, safety measures have a significant impact on the physical, social, and digital service experience of visitors in theme parks [1].

2.2. Special design requirements for amusement equipment

The mechanical structure design of amusement rides has unique requirements due to their special operating environment and mode. Impact loads are a crucial factor that must be considered in the design of amusement rides. For example, roller coasters generate significant impacts during high-speed travel and sudden braking, which requires the structure to have sufficient strength and rigidity to withstand these forces and prevent deformation or damage [2]. Alternating stress is also a key issue. Frequent starts and stops, as well as periodic motion of the equipment, can produce alternating stress. Long-term exposure to such stress may lead to structural fatigue failure. Therefore, fatigue-resistant properties must be considered in material selection and structural design. Human-machine interaction characteristics also impose constraints on the design. The equipment must ensure the safety and comfort of passengers. For instance, rational seat design and the installation of safety devices need to be integrated into the structural design. These requirements are not only based on the actual operating needs of amusement rides but also strictly follow relevant regulatory requirements and technical specifications. As pointed out by research, the mechanical structure design of amusement rides needs to meet strict regulatory requirements and technical specifications to ensure their safety and reliability.

3. Structural safety assessment method system

3.1. Analysis of existing evaluation methods

Finite element simulation is widely applied in the structural safety assessment of amusement rides. It can simulate the stress and strain distribution of the equipment under various working conditions, providing a basis for design optimization [3]. However, the accuracy of its model establishment depends on material parameters and boundary condition settings, which may deviate from the actual situation. Physical testing can directly obtain the actual performance data of the equipment, such as strength and stiffness tests, but it is costly, time-consuming, and difficult to fully simulate for some complex working conditions. Fault tree analysis, on the other hand, starts from the perspective of system failure. Through logical reasoning, it identifies the causes and combinations that may lead to failure, which helps to recognize potential risks. But for complex amusement ride systems, establishing a fault tree may be challenging, and it is difficult to quantitatively analyze the impact of each factor on structural safety.

3.2. Limitations of assessment methods

There are certain limitations in the methods of structural safety assessment. In terms of dynamic loads, existing methods fall short in considering their time-varying characteristics and fail to accurately simulate the complex changes of loads under actual working conditions, which affects the accuracy of the assessment [4]. The evaluation of material performance degradation is also not comprehensive enough. It is difficult to fully take into account the changes in material properties caused by factors such as fatigue and corrosion during long-term use, which may lead to underestimating the potential risks of the structure. Furthermore, current assessment methods are also insufficient in dealing with complex structures and multi-physics coupling problems. For example, when multiple types of loads (such as wind loads and vibration loads) commonly seen in amusement rides act simultaneously, existing methods find it hard to accurately assess their impact on the overall structural performance. These problems not only affect the reliability of the assessment results but may also lead to safety hazards in the actual operation of the equipment. Therefore, there is an urgent need to further research and improve assessment methods to better meet the needs of structural safety assessment in the mechanical design of amusement rides and ensure the safe operation of amusement rides.

4. Construction of safety assessment system

4.1. Establish an evaluation index system

4.1.1. Principles of indicator selection

The selection of structural safety assessment indicators for the mechanical design of amusement rides needs to follow principles such as scientific validity, systematicness, and feasibility. Scientific validity requires that the indicators accurately reflect the structural safety characteristics of amusement rides, and determine quantitative standards based on principles of mechanics and engineering practice, such as determining reliability indicators through stress analysis [5]. The principle of systematicness emphasizes the interconnection and complementarity among indicators, forming a complete system that covers all levels from the entire equipment to individual components. Feasibility focuses on the operability of the indicators in actual assessment, considering the ease and cost of data acquisition to ensure effective implementation of the assessment.

At the same time, the particularities of amusement rides must also be taken into account, such as the indirect effects of factors like passenger experience and appearance design on structural safety, to comprehensively determine the quantitative standards for core indicators. On top of that, during the process of indicator selection, it is also necessary to fully combine the actual operating environment and frequency of use of amusement rides. For example, for frequently used amusement rides, more attention should be paid to indicators related to fatigue life and dynamic performance. For equipment installed outdoors, environmental factors (such as wind loads and temperature changes) that affect structural safety need to be considered, so as to more comprehensively reflect the safety status of the equipment in actual use and provide strong support for the safe operation of amusement rides.

4.1.2. Multi-level indicator system

A hierarchical evaluation system that includes the strength of the main structure, the reliability of connectors, and the effectiveness of safety devices should be established. The strength of the main structure is the foundation of the safety of amusement rides, and factors such as material properties and the rationality of structural design should be considered to ensure that it can withstand the expected loads under various working conditions [6]. The reliability of connectors is crucial, as their quality and connection methods directly affect the overall structural stability. The strength and fatigue life of connectors should be assessed. The effectiveness of safety devices is related to the life safety of visitors, including guardrails, seat belts, etc., and it should be checked whether they meet relevant standards and can effectively prevent visitors from accidentally contacting hazardous parts. By comprehensively evaluating these aspects and establishing a scientific and rational multi-level indicator system, a comprehensive safeguard for the structural safety of amusement rides can be provided.

4.2. Evaluation model construction

4.2.1. Multi-physical field coupling modeling

During the operation of amusement rides, multiple physical fields such as mechanics, kinematics, and thermodynamics interact with each other. To accurately assess their structural safety, it is necessary to establish a digital simulation model that couples mechanics, kinematics, and thermodynamics. The mechanical structural characteristics of the equipment, including the material properties, geometric shapes, and connection methods of the components, should be comprehensively considered, as these factors directly affect the deformation and stress distribution of the equipment under load [7]. Meanwhile, kinematic parameters such as velocity, acceleration, and displacement are crucial to the dynamic response of the equipment and interact with the mechanical structure. Besides, thermodynamic factors, such as heat generation from friction and changes in ambient temperature, can also alter the material properties and stress state of the equipment. By coupling these physical fields, a more realistic simulation of the complex working conditions of amusement rides in actual operation can be achieved, providing a more reliable basis for structural safety assessment.

4.2.2. Model validation method

Comparing the actual measurement data of roller coaster tracks with simulation results is an important method to verify the validity of the model. In practice, it is necessary to first obtain the actual measurement data of the roller coaster track during operation, including key parameters such as speed, acceleration, and stress [8]. At the same time, use the established evaluation model to carry out corresponding simulation calculations to obtain the theoretical values of various parameters. Following that, a detailed comparative analysis between the actual measurement data and the simulation results is then conducted. If the two are highly consistent within a reasonable error range, it indicates that the model can effectively reflect the actual situation and has high accuracy and reliability. If there is a significant difference, the model needs to be further revised and improved until it can meet the needs of practical application.

5. Structural safety improvement measures

5.1. Material optimization strategy

5.1.1. Application research of high strength steel

The high-strength steel S690QL has significant advantages in the lightweight design of amusement ride support structures. Its high-strength characteristics allow for a reduction in material usage while meeting structural strength requirements, thereby lowering the structure's own weight [9]. This not only helps to reduce energy consumption during equipment operation but also enhances the dynamic performance of the equipment to some extent. In the meantime, the good toughness and fatigue resistance of high-strength steel can enhance the reliability and durability of the structure under complex loading conditions, reducing safety risks caused by fatigue crack propagation and providing strong support for the long-term safe and stable operation of amusement rides.

5.1.2. Composite material process improvement

Carbon fiber-reinforced plastics play an important role in the protective devices of amusement rides, and their interfacial reinforcement technology is the key. By optimizing the interfacial bonding between fibers and the matrix, the overall performance of the material can be improved. On one hand, surface treatment technologies can be used to improve the surface properties of fibers, enhancing their compatibility and adhesion with the matrix [10]. For example, methods such as chemical etching and plasma treatment can be used to remove impurities from the fiber surface, introduce reactive functional groups, and promote chemical reactions with the matrix. On the other hand, the rational selection of matrix materials and additives is also crucial. A matrix with good fluidity and wettability should be chosen to ensure that it can fully fill the gaps between fibers.

Coupling agents and other additives should also be added to further enhance the interfacial bonding strength, thereby improving the structural safety and reliability of the protective devices. In practical applications, the durability and environmental adaptability of the material also need to be considered. For example, for protective devices used outdoors, it is necessary to ensure that the material can maintain its excellent performance after long-term exposure to natural environmental conditions such as ultraviolet light and wind and rain. Therefore, weather-resistance-modifying measures should also be combined in interfacial reinforcement technology to ensure that the protective devices can provide reliable protection throughout the service life of the amusement rides.

5.2. Structural topology optimization

5.2.1. Parametric modeling method

The size optimization of the rotating flying chair frame structure on the Isight platform is carried out through a parametric modeling approach. An initial structural model is created using professional modeling software, and key design variables, such as member length, diameter, and wall thickness, are defined as adjustable parameters for optimization. Parametric modeling enables rapid and precise modification of geometric features, allowing structural dimensions to be efficiently updated to meet varying design requirements. The model is then integrated with the Isight platform, where built-in optimization algorithms iteratively adjust parameter values. Throughout this process, critical performance indicators, including structural strength, stiffness, and stability, are evaluated to ensure compliance with safety standards. Through repeated iterations, the design variables are refined until an optimal configuration is achieved, enhancing both the structural topology and the overall safety performance of the rotating flying chair frame.

5.2.2. Fatigue life improvement program

The use of shape-memory alloys to achieve adaptive reinforcement at critical connection points is an important measure to enhance the structural safety of amusement rides. Shape-memory alloys have unique shape-memory effects and super-elastic properties. When used at critical connection points of amusement rides, these alloys will undergo phase changes and produce adaptive shape changes or stress adjustments in response to temperature variations or stress stimuli when the equipment is subjected to abnormal loads or vibrations. This adaptive reinforcement mechanism can effectively absorb and disperse stress concentrations, preventing the connection points from being damaged due to long-term fatigue or sudden overloading. For example, in complex joint connections or high-stress-transfer areas, shape-memory alloys can adjust their own properties in real-time according to actual working conditions, ensuring the reliability and stability of the connections and thereby enhancing the overall structural safety and fatigue life of the amusement rides.

5.3. Redundant design innovation

5.3.1. Multi-protection mechanism design

The structural safety in the mechanical design of amusement rides is of utmost importance. Developing a mechanical-electrical dual-redundancy emergency braking system is an innovative and effective multi-protection mechanism. In the mechanical aspect, multiple independent braking devices are installed, such as combining different types of mechanical braking structures, like disc brakes and drum brakes. When one braking device fails, the others can still function properly to ensure that the equipment can stop in time. In the electrical aspect, a dual-path control system is used, including independent sensors, controllers, and actuators. When one electrical system fails, such as a sensor malfunction or controller failure, the other system can immediately take over and trigger the emergency braking command, ensuring the structural safety of the amusement rides in various emergency situations.

5.3.2. Modular replacement solution

The innovation of redundant design and the modular replacement scheme are crucial for improving the structural safety of amusement rides. For redundant design innovation, multiple identical or similar structural components can be installed at key locations. When one component fails, the others can continue to perform the corresponding functions, ensuring that the overall operation of the equipment is not significantly affected. For example, additional backup support beams can be added to certain critical support structures. In terms of the modular replacement scheme, introducing a rapid replacement and maintenance system for track connection nodes is a significant measure. Designing track connection node modules that are easy to disassemble and install allows maintenance personnel to quickly locate and replace the modules when problems occur. This reduces repair time and equipment downtime, enhances the utilization efficiency and safety of the equipment, and also facilitates routine inspection and maintenance work.

6. Conclusion

The structural safety in the mechanical design of amusement rides is of utmost importance. The assessment method based on multidisciplinary simulation can take into account a variety of factors and effectively enhance the reliability of the equipment. Through this method, the performance of amusement rides under various working conditions can be simulated and analyzed to identify potential safety hazards in advance, providing a basis for structural optimization. In the future, with the development of technology, the focus should be on developing real-time health monitoring systems based on the Internet of Things (IoT). With the help of IoT technology, real-time operation data of the equipment can be obtained to achieve dynamic monitoring of the equipment status and timely warning of failures. Meanwhile, introducing machine-learning algorithms into the life-prediction models is also an important research direction. Machine-learning algorithms can handle a large amount of complex data and more accurately predict the equipment's life, providing scientific guidance for equipment maintenance and renewal, and further ensuring the structural safety of amusement rides.

Disclosure statement

The author declares no conflict of interest.

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