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Review and Prospect of Research on Structural Health Monitoring Technology for Bridges

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Abstract: As a crucial infrastructure in the transport system, the safe operation of bridges is directly related to all aspects of people's daily lives. The development of bridge structural health monitoring technology and its application play an important role in ensuring the safety and extending the service life of bridges. This paper carries out in-depth research and analysis on the related technology of bridge structural health monitoring. Firstly, the existing monitoring technologies at home and abroad are sorted out, and the advantages and problems of various methods are compared and analyzed, including nondestructive testing, stress measurement, vibration characteristic identification, and other commonly used monitoring technologies. Secondly, the key technologies and equipment in the bridge health monitoring system, such as sensor technology, data acquisition, and processing technology, are introduced in detail. Finally, the development trend in the field of bridge health monitoring is prospected from both theoretical research and technical application. In the future, with the development of emerging technologies such as big data, cloud computing, and the Internet of Things, it is expected that bridge health monitoring with intelligent and systematic features will be more widely applied to provide a stronger guarantee for the safe and efficient operation of bridges.

Keywords: Bridge structural health monitoring; Safe operation; Monitoring technology

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1. Introduction

Bridges are an important symbol of human civilization and technological progress and one of the most important infrastructures in the modern transport system. According to the data provided by the Public Works Department (PWD), the total length of bridges around the world has reached tens of millions of kilometers and is expected to continue to grow in the coming years. Therefore, the safety and stability of bridges are of great importance to the national economy and social life. As the level of design and construction continues to improve, the types and structures of new bridges are becoming more and more complex, making bridge health monitoring an even greater challenge. The research and application of health monitoring technology are of great practical value for bridge structures that are subjected to long-term complex environmental conditions and multiple loads.

2. Current status and development of bridge health monitoring technology

2.1. Overview of bridge health monitoring techniques

Bridge health monitoring technology is a brand-new technical method that came into being in recent years, which mainly uses modern scientific and technical methods to monitor the working performance of bridges, so as to discover the lesions of bridges in time and take corresponding repair or reinforcement measures to guarantee the normal use and safety of bridges [1].

The core concept of bridge health monitoring technology is to collect a large amount of data from bridges during operation by monitoring and analyzing the bridges on a full-time, all-weather basis, and applying modern scientific and technological methods, such as multimodal signal processing, artificial intelligence, and machine learning, to carry out in-depth data analyses and research, so as to obtain an accurate diagnosis of the bridge's health condition [2].

Bridge health monitoring technology generally includes the following aspects: structural performance monitoring, environmental impact monitoring, stress-strain monitoring, vibration characteristics monitoring, and damage identification. Structural performance monitoring involves monitoring various performance parameters of the bridge, including but not limited to displacement, deformation, crack width, and other structural performance parameters. Environmental impact monitoring is mainly to monitor the environmental factors affecting the health condition of the bridge, including but not limited to temperature, humidity, wind load, etc [3]. Stress-strain monitoring and vibration characteristic monitoring, on the other hand, mainly monitor the internal stress and vibration characteristics of the bridge to obtain the health status of the bridge. Injury identification, on the other hand, identifies possible injuries to the bridge by analyzing the monitored data [4].

The purpose of bridge health monitoring is to timely and accurately grasp the health condition of bridges, to guide the repair and reinforcement of bridges, and to avoid major accidents caused by bridge health problems. Bridge health monitoring technology also provides an effective means for the scientific management of bridges, and lays a solid foundation for improving the service life of bridges and enhancing economic benefits [5]. In future development, with the continuous development and updating of science and technology, the bridge health monitoring technology will also undergo profound changes to provide more effective and accurate monitoring methods.

2.2. Current status and development of bridge health monitoring technology at home and abroad

Bridges are an important part of urban infrastructure, and with urban development and the increase in traffic demand, the number and scale of bridges are growing dramatically. Accordingly, bridge health monitoring technology is also developing rapidly and has become an important field of bridge engineering technology research [6].

At present, the international advanced bridge health monitoring technology plays a pivotal role in bridge design, construction, and operation, which is mainly reflected in the following three aspects: it is the establishment of a bridge health monitoring system, which monitors the operational status of the bridge in real-time by installing sensors and data collection equipment [7], including strain gauges, acceleration sensors, and displacement sensors. The collected data are then processed and analyzed using complex algorithms and models, such as artificial neural networks, genetic algorithms, etc., to assess the bridge's health status [8]. Based on the assessment results, repairs and maintenance are carried out to ensure the safe operation of the bridge.

In China, due to the limitations of technology and equipment, the application of bridge health monitoring technology is not widespread. However, in recent years, with the improvement of domestic technology research and development level and the development of wireless communication technology, bridge health monitoring technology is gradually gaining popularity and application [9]. At present, domestic bridge health monitoring technology mainly focuses on real-time monitoring and data processing, and analysis of bridges and has played an important role in the operation of some important bridges.

Bridge health monitoring technology faces some challenges both at home and abroad, such as huge data volume, complex processing, and high cost of sensors. Therefore, future development trends should strive to optimize and improve the existing technology, improve the data processing efficiency, and reduce the cost of sensors, so as to promote the wide application of bridge health monitoring technology [10].

Looking ahead, with the development of emerging technologies such as big data and cloud computing, bridge health monitoring technology is expected to achieve more efficient data processing and analysis, and provide more accurate bridge health status assessment. The application of IoT technology will make the bridge health monitoring system able to monitor the bridge status in real-time and comprehensively, so as to realize the intelligence and systematization of bridge health monitoring [11].

2.3. Analysis of the advantages and problems of bridge health monitoring technology

The adoption of bridge health monitoring technology offers a series of advantages. These advantages are mainly reflected in the following aspects: early detection of structural problems and improve the service life and safety of bridges. Through real-time monitoring of bridges, structural problems can be detected and repaired in a short time at the early stage of formation, which can greatly extend the service life of bridges and reduce the possibility of safety accidents caused by structural problems [12]. Effective reduction of maintenance costs. Timely failure prevention and maintenance can avoid excessive maintenance behavior and save maintenance costs. Effective diagnosis of accident causes. By analyzing the bridge health monitoring data, the cause of the accident can be clarified so that it can be repaired more quickly and effectively to avoid the recurrence of similar problems.

Despite the numerous advantages and conveniences offered by this technology, some of the more notable issues and challenges have arisen during its practical application. One of the key issues is the selection and configuration of sensor technology. The implementation of bridge health monitoring often requires a large number of sensors to monitor various aspects of the situation, how to correctly and reasonably select and configure sensors is an extremely important issue. Unreasonable selection and configuration will affect the effectiveness and accuracy of monitoring. Another major issue is the processing and analysis of large amounts of data, which not only requires efficient algorithms and computer hardware support but also professional personnel to interpret and judge the data. What's more, due to the many dynamic environmental factors involved in the application stage of the monitoring technology, the influence of various uncertainties on the monitoring results is also a subject worthy of in-depth study [13].

The above two major problems have, to a certain extent, constrained the further improvement of bridge health monitoring technology. This also suggests for future research directions that the existing bridge health monitoring technology needs to be optimized and improved in depth, especially in terms of the selection and configuration of sensor technology, as well as data processing and analyses, more targeted and efficient solutions are needed so as to improve the system and convenience of bridge health monitoring [14].

3. Key technologies and equipment for bridge health monitoring

Bridge health monitoring key technology and equipment are an important part of the bridge health monitoring system, mainly including sensor technology, data acquisition and processing technology and non-destructive testing, stress measurement, vibration characteristic identification, and other commonly used monitoring technology.

Sensors are the core of the whole monitoring system that affects the reliability and accuracy of monitoring data. Currently, sensors are mostly applied in the monitoring of stress, crack, displacement, temperature, and environmental factors of bridges. According to the special structure and environment of bridges, the type and location of sensors need to be carefully designed. At present, common bridge health monitoring sensors mainly include strain gauges, displacement gauges, vibration sensors, meteorological sensors, etc., while fiber-optic sensors and electromagnetic wave sensors are also used for special needs.

Data acquisition and processing technology is a key link in bridge health monitoring. How to accurately collect, timely, and effectively process these data is directly related to the assessment results of bridge health conditions [15]. At present, the data collection of bridge health monitoring mostly adopts online and real-time methods, and the data are sent to the special data processing center for analysis and processing through transmission equipment to achieve the dynamic assessment of bridge health condition. In data processing technology, data mining, machine learning, pattern recognition, and other technologies are used to improve the efficiency and accuracy of data analysis. Deep learning, neural networks, and adaptive algorithms also play an important role in the data processing of bridge health monitoring.

Commonly used non-destructive testing (NDT), stress measurements, and identification of vibration characteristics are the primary means of bridge health monitoring. Nondestructive testing techniques allow for a variety of tests and assessments to be performed without damaging the bridge structure. Examples include the acoustic wave method, thermal infrared method, and laser scattering method. Stress measurement, on the other hand, monitors the magnitude of extrinsic stress in a bridge as a means of determining the fatigue and damage level of the bridge. Vibration characteristic identification, on the other hand, makes use of the bridge's own vibration changes under the weight change of the load carried, wind speed, temperature, and other environmental changes to carry out characteristic analysis [16].

Technical equipment and professional personnel are the two cornerstones of bridge health monitoring development, technical equipment follows the rapid pace of scientific and technological development and is constantly upgraded to meet the increasingly complex monitoring needs. With specialized field operation technicians and data processors, the quality and real-time performance of bridge health monitoring data can be ensured.

4. Future development trends and outlook of bridge health monitoring technology

4.1. Development trend of bridge health monitoring based on big data, cloud computing, Internet of Things, and other emerging technologies

With the development of big data, cloud computing, the Internet of Things, and other emerging technologies, bridge health monitoring technology will achieve leapfrog development. The use of big data technology allows large-scale and comprehensive information analysis and processing, allowing for a more accurate evaluation of bridge health [17]. The application of cloud computing technology will eliminate the need for local processing and storage of bridge health monitoring data, which will reduce equipment investment and improve the efficiency and safety of data processing and storage. On the other hand, the application of IoT technology can be used to collect and transmit various indicators of bridge safety operation in a continuous and real-time manner, so as to realize the accurate monitoring of bridge health conditions [18].

4.2. Prospects for intelligent and systematic development of bridge health monitoring

The future bridge health monitoring will not only be a single technology or tool but also a comprehensive and systematic solution that integrates many high technologies (e.g. artificial intelligence, big data, IoT technology, etc.). The introduction of intelligent technology will make bridge health monitoring more intelligent, such as through deep learning and other technologies to achieve automatic identification and prediction of bridge health conditions [19]. The systematic development can achieve the synergy and integration of all aspects and levels of bridge health monitoring, so as to form a comprehensive and in-depth bridge health monitoring system, which can monitor and assess the health condition of bridges in an all-round way.

4.3. Vision and recommendations for the safe operation of bridges in the future

The continuous development of technology will provide unprecedented opportunities and challenges for bridge safety operations. On the one hand, the continuous development and application of emerging technologies will enable the accuracy and efficiency of bridge health monitoring to be significantly improved, thus significantly increasing the operational safety and service life of bridges [20]. On the other hand, the in-depth application of these new technologies also brings many challenges, such as the difficulties in processing and analyzing big data, and the degree of understanding and mastery of the new technologies and their applications. It is recommended that the relevant departments should strengthen the research on new bridge health monitoring technologies and promote the innovation of bridge health monitoring, and also need to focus on the cultivation and introduction of talents to meet the new demands brought about by the technological development.

5. Conclusion

This paper provides a comprehensive overview of the relevant development, application, and future development trends of bridge structural health monitoring technology. For the main technical means of bridge health monitoring, such as nondestructive testing, stress measurement, and vibration characteristic identification, this article provides a comprehensive analysis and comparison from both theoretical and practical perspectives. In addition, we have also discussed in depth the key technologies and equipment in bridge health monitoring systems, such as sensor technology, data acquisition and processing technology. However, despite the progress that has been made, there are still the following challenges in bridge structural health monitoring: (1) effectively managing and operating a large-scale bridge health monitoring system, (2) further improving sensor technology, data acquisition, and processing technology; and (3) integrating emerging technologies such as the Internet of Things (IoT), big data, and cloud computing into bridge health monitoring to achieve the bridge intelligent and systematic health monitoring. In the future, bridge structural health monitoring is expected to develop in a more intelligent and systematic direction. The wide application of emerging technologies in this field will provide a stronger guarantee for the safe and efficient operation of bridges. Additionally, the participation of more researchers and engineers in the research and practice of this field is anticipated, jointly promoting the development of bridge structural health monitoring technology.

Disclosure statement

The author declares no conflict of interest.

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