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Research on structural health monitoring methods for bridge structures

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Abstract. With the development of science and technology, China is building more and more Bridges. The inspection and maintenance of bridge during operation plays an important role in the safety of bridge. Firstly, the research background and significance of bridge structure health inspection are introduced, and the research status and progress of health inspection are analyzed. Then, several commonly used monitoring methods are listed. Based on the comprehensive study of the bridge health monitoring system, the main conclusions are as follows: the bridge health monitoring system is realized through the coordination of several subsystems, including: bridge working environment monitoring, bridge structure overall performance monitoring and bridge structure local performance monitoring. The bridge structural health monitoring system is mainly used in bridge damage identification and bridge safety warning. The bridge structure health monitoring system conforms to the development trend of high technology and will become an indispensable part of the bridge operation in the future.

Keywords: bridge structural health monitoring, damage identification, security warning, data management system.

1. Introduction

Since 2000, China has vigorously developed and built many roads and bridges. As an important part of transportation, bridge facilitates people's life and promotes economic development. By 2020, China had surpassed the United States in the number of bridges in service, becoming the first in the world. It has a population of 912,800 and a total length of 6,628.55 meters. Among them, the number of dedicated bridges reaches 11629,700 meters, with a total of 6,444 bridges [1]. With the continuous development of bridge construction, the problem of bridge safety has also been highlighted. Traditionally, health checks are carried out on bridge structures, such as routine disease checks and bridge appearance checks. However, this annual or biennial inspection can still cause some problems to be missed. If danger occurs, the loss will be incalculable. Bridge structural health monitoring uses electronic means and high-tech sensing devices to obtain real-time response of bridges. Through the rational use of many new technologies, good monitoring of bridges can be achieved, helping to obtain accurate data faster and better and respond. Combining regular bridge health inspections with real-time health monitoring will ultimately improve bridge safety.

Structural health monitoring systems in some developed countries started earlier, such as the Sunshine Viaduct in the United States, the Tampico Cable-stayed Bridge in Mexico, the Akashi Strait

Bridge in Japan, and the Great Belt East Suspension Bridge in Denmark [2]. Although China's bridge health monitoring technology started late, with the unremitting efforts of Chinese scholars in theoretical basis and application, China has also tried and gradually skilled in installing bridge structural health monitoring systems, such as Tsing Ma Bridge and Hong Kong Dafo Yangtze River Bridge [3-4]. Bridge structural health monitoring systems are becoming more and more popular and practical. With the popularity of bridge health monitoring, using cutting-edge technology, remote monitoring can be carried out without leaving home. In the past, bridge health monitoring methods mainly included convergence instrument, level instrument, total station instrument, etc. [5-7]. Although these methods are more practical, they cost a lot of manpower and material resources and are not cost-effective [8-9]. Traditional detection technology has many inconveniences. The use of manual visual inspection and carrying some simple instruments to rule out problems requires a long time and outdated means of monitoring, and is costly and dangerous to workers. The amount of time spent on monitoring also varies greatly, depending on each company's monitoring system, and there is no uniform standard. This traditional detection technology not only costs a lot of money and time, but also its subjective and scientific significance is very different from that of modern monitoring.

Nowadays, with the development of modern technology, many new scientific technologies such as accelerometers, optical fiber strain measurement, global satellite navigation, close-up photogrammetry, and three-dimensional laser scanning have emerged one after another [10-13]. With the advanced measurement technology, high quality measurement technology, efficient data transmission technology and the wide application of smart materials and precision sensing instruments, the bridge health monitoring system has gradually matured and developed. This system provides a scientific and reliable basis for the maintenance and repair of Bridges and ensures the safe operation of Bridges during their service life [14].

This paper firstly introduces the research background and significance of bridge structure health inspection, and analyzes the research status and progress of health inspection. Several commonly used monitoring methods are listed, and their advantages and disadvantages are analyzed to provide effective reference for the establishment of bridge health monitoring system.

2. Structural health monitoring systems for bridges

2.1. Overview of structural health monitoring systems for bridges

The vehicle for the health monitoring of bridge structures is the health monitoring system. This system contains a combination of knowledge from several fields, as well as multiple monitoring projects taking place simultaneously. As shown in Figure 1, the bridge structural health monitoring system relies on the simultaneous collaboration of several subsystems. For example, the sensor subsystem is the basis for a hardware system whose main purpose is to measure changes in environmental loads and structural hydrostatic forces during the operation of the bridge. The data acquisition and transmission system transmit the data to the monitoring center by wired or wireless means and uses programming to convert, filter, noise reduction and analyze the raw signals to obtain valid information data on the structural condition of the bridge. The structural assessment subsystem uses the results obtained from the data processing and analysis subsystem, combined with data models, bridge characteristics, and relevant codes, to analyze and identify load damage to the bridge and provide a scientific basis for the management and maintenance department. The data management subsystem uses databases and other means to store and manage the collected data and processing results, analyze and identify damaged information, and provide a scientific basis for the management and maintenance departments. The data management subsystem uses databases and other means to store and manage the collected data and processing results, analyze and identify damaged information, and provide a scientific basis for the management and maintenance departments. The data management subsystem uses a database to store and manage the collected data and processing results. The stored information includes information on the bridge structure, raw sensor data, external load and structural static dynamic response information, and damage assessment and analysis results. The various subsystems of the bridge structural health monitoring system are closely linked to each other and are currently widely used.

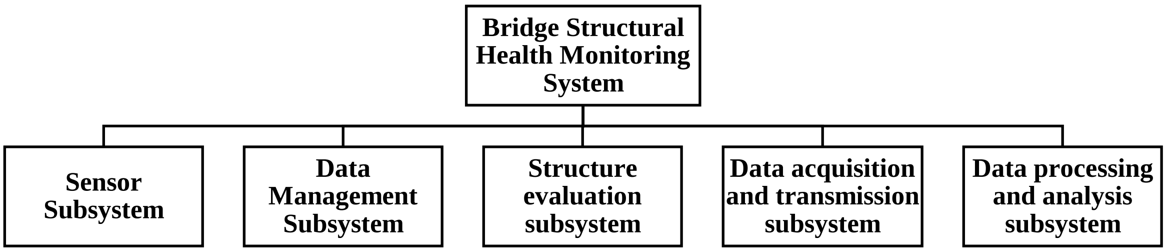

Figure 1. Bridge health monitoring system [15].

2.2. Current status and developments in research

In China, the bridge industry has also been unprecedented development. At the same time, the bridge health monitoring system has been in the forefront of the world.

(1) The development trend of structural monitoring is from a single subject with limited scope to a comprehensive and systematic whole-bridge monitoring and unified management.

(2) The health assessment system has changed from a single data collection to an increasingly complex post-processing and analysis of data.

(3) The system is more advanced, reliable and safe.

(4) The development trend is international level and international cooperation.

(5) The system has a better interface and practicality, which can significantly reduce the workload and learning costs of the operator.

2.3. Classification of bridge health monitoring systems

As shown in Table 1, the bridge health system can be divided into three main monitoring programs. The first one is the bridge working environment monitoring, including the monitoring of the bridge site wind field characteristics, environmental temperature and bridge temperature distribution, as well as the monitoring of traffic vehicle load information, earthquake load and ship impact load. The second is the monitoring of the overall performance of the bridge structure, such as the geometric line monitoring of the main load-bearing components of the bridge, the vibration monitoring of the bridge structure. Finally, it is the monitoring of the local performance of the bridge structure, such as the monitoring of the special parts of the stress, the monitoring of the vibration of important components, the monitoring of the durability of structural materials, and the monitoring of the bridge ancillary facilities.

Table 1. Classification of bridge health monitoring systems [16].

Monitoring Projects	Categories
Bridge Working environment monitoring	Monitoring of wind field characteristics at the bridge site
	Traffic vehicle load information monitoring
	Earthquake load and ship impact load
	Ambient temperature and bridge temperature distribution monitoring
	Other
Bridge structure overall performance monitoring	Geometric line monitoring
	Force monitoring of the main load-bearing elements of bridges
	Bridge structure vibration monitoring
	Other monitoring items

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Table 1. (continued).

Bridge structure local performance monitoring	Special parts force monitoring Vibration monitoring of critical components Structural material durability monitoring Bridge appurtenances monitoring

3. Application of bridge health monitoring system

3.1. Damage identification of bridges

Generally, damage identification is accomplished by establishing finite element model and conducting simulation analysis. By observing different damage states, examining static and dynamic test indexes, the sensitivity of damage indexes to damage was studied. Both can identify damage, but different tests have different conditions. For example, the former requires more sensors to be laid out, and there may be instrument failures or identification failures, and a high level of machine accuracy is required. Therefore, when the sensor is not sensitive, there may be small damage. For dynamic testing, it is easier to identify damage and the data is more readily available, but other tools, such as neural networks, are needed to identify damage more accurately.

In the cable-stayed bridge structure, the stress forms of the main beams in the cable-stayed anchorage area and the non-cable-stayed anchorage area are significantly different. In short-pylon cable-stayed Bridges, the cable structure is more inclined to external prestressing, which makes the length of cable anchorage area shorter than that of full cable-stayed Bridges. At the same time, the main beam of the structure is subjected to compressive stress and bending force. Due to the complexity of structural forces, the traditional damage identification indexes are not sensitive enough to the damage in the whole range of such Bridges. In fact, it is also clear from the previous index calculation that the bending curvature difference method cannot detect damage at 110 m. or the main beams of short-tower cable-stayed Bridges, according to the characteristics of different stress fields, different indexes or different modal data amounts are used for damage identification to achieve accurate damage diagnosis [17]. In the two-point damage identification test, the uniform distribution load method has better identification effect and lower error for larger damage cases. However, when the damage is mild, it is still difficult to identify the location of the damage according to the trend of the index curve. The flexural curvature difference method is not sensitive enough to the damage of cable-free area at the top of pier, and the fluctuation error is large. In addition, if the two damage sites are close, the mutation point of the larger damage may mask the mutation point of the smaller damage, resulting in the failure to determine the fluctuation of the smaller damage, and it is easy to be misdiagnosed as the fluctuation error caused by the larger damage.

When the damage identification of such Bridges is carried out, the uniform distribution load method should be the main identification method, and the bending curvature method should be the auxiliary method. Most damages can be identified using low-order modal data. At the same time, the damage should be identified and treated as early as possible to avoid the accumulation of multiple injuries, which is difficult to identify with indicators.

3.2. Safety warning for bridges

The basic principle of the bridge monitoring system is to collect the basic state data, structure monitoring data, maintenance history data of the bridge, and establish the bridge early warning database. The system then monitors and collects safety monitoring data in real time to determine the safety status of the bridge, the extent and extent of damage The system uses multiple sensors to monitor and collect data on vibration, temperature and other parameters of the bridge structure in real time. Once the system detects abnormal conditions such as structural deformation, vibration exceeding a threshold or abnormally high

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temperature, the system will immediately issue a safety warning signal. These early warning signals are then used to issue timely forecasts, and the relevant authorities take immediate action to prevent the occurrence of safety accidents.

In addition to real-time alarm, the system also supports remote monitoring and access functions. It also helps with monitoring and management so that the health and warning information of the bridge can be viewed remotely at any time. This greatly improves the efficiency and responsiveness of bridge safety monitoring. According to the severity and urgency of safety risks, bridge safety warning levels are divided into 1, 2, 3 and 4 levels. The specific description of each warning level is shown in Table 2.

To solve the problems of bridge health monitoring in practical engineering applications, such as the difficulty of deploying terminals and the backwardness of collection and transmission methods, the model of "front-end optimization and back-end upgrade” can be adopted for optimization [18]. The application of the lightweight bridge structural health monitoring system systematically alleviates bridge safety.

Table 2. Security alert levels.

Serial number	Level	Description
1	Level 1 warning	The bridge has experienced severe structural deformation, severe vibration or other emergency that endangers the integrity and safety of the bridge. In this case, the bridge may be at risk of collapse or serious damage, requiring immediate emergency measures to stop traffic and evacuate nearby people.
2	Level 2 warning	Situations where the bridge has a high safety risk, such as moderate structural deformation, vibration or temperature anomalies beyond the normal range. In this case, the bridge may have certain structural problems or potential risks, and timely measures need to be taken for overhaul and maintenance to ensure the safe use of the bridge.
3	Level 3 warning	Situations where the bridge presents a general safety risk, such as slight structural deformation, mild vibration, or slightly higher temperature. In this case, the bridge may have some normal wear or minor structural issues that require daily monitoring and routine maintenance to ensure the normal operation of the bridge.
4	Green statues	The system analyzes that the bridge is in normal operating condition.

Operation problems is shown as Figure 3. Specifically, with the cloud platform as the core, the new generation of road and bridge intelligent monitoring instruments and the upgraded back-end system are integrated in the front end. AIoT Open platform (PaaS) and Road and Bridge Health Monitoring and Safety early warning System (Saa8) constitute a new road and bridge health monitoring and safety early warning cloud platform. Through this platform, the safe operation of the bridge can be fully guaranteed [19].

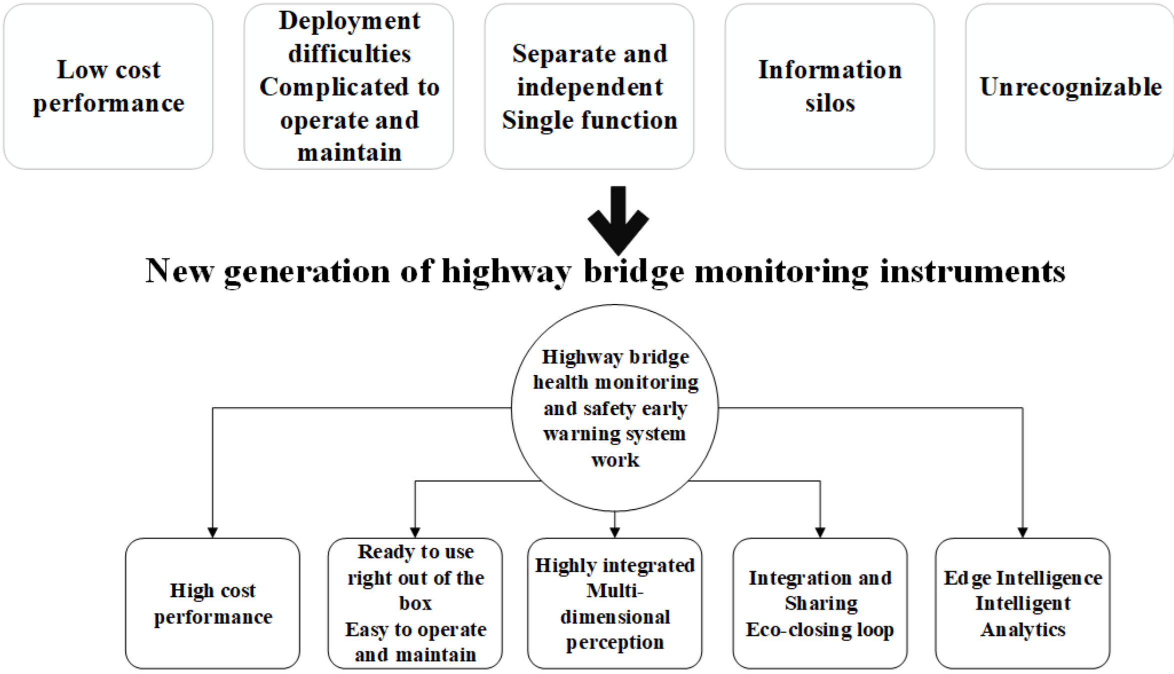

Figure 2. Bridge health monitoring and safety early warning system project [19].

The structural health monitoring system of the bridge cluster in Pinghe County is a typical application case of the new generation of highway bridge intelligent monitoring instruments and the cloud platform for highway bridge health monitoring and safety warning. The system deploys new-generation highway bridge intelligent monitoring instruments, weather environment and video monitoring, and other sensing terminals at key locations of bridge structures in Pinghe County to collect real-time static, dynamic, environmental, and load information of bridges within Pinghe County. This data provides the basis for safety warnings and safety analysis and assessment of highway bridges, enabling us to keep abreast of defects and damage to bridge structures and to assess their development trends and potential risks that may be posed to the safe operation of the structures under specific environmental conditions. Such a system enables the monitoring and management of the full life cycle of highway bridge structures [19]. By creating a structural health monitoring system for the bridge complex in Pinghe County, safety monitoring has been provided for five important highway bridges within the county. The system has successfully warned of eight incidents of large vehicles illegally boarding the bridges and provided 12 bridge maintenance recommendations to bridge operation and maintenance units. To a certain extent, this has improved the safety and durability of the five important highway bridges in Pinghe County, serving an area of 253 square kilometers and 270,000 people [19].

4. Conclusion

This paper mainly introduces the method and research of bridge health monitoring, and introduces the significance of bridge health monitoring. Through some monitoring examples, the concept and application of bridge health monitoring damage identification are put forward. Taking a bridge in Pinghe County as an example, the application of bridge health monitoring system in safety early warning is further explained. The new generation of intelligent monitoring instruments for highway Bridges is more convenient and safer, improves safety to a certain extent, and facilitates the public.

Future bridge health monitoring systems require the development of high-tech technologies, such as drones, intelligent robots and other technologies. These technologies have the potential to significantly improve the accuracy and speed of bridge health monitoring, damage identification and safety warning.

They can also learn deeply on their own, and then leverage future big data processing technologies to facilitate the formation of diverse analytics. At present, bridge safety monitoring is gradually developing in the direction of standardization, systematization and informatization, and it will become an indispensable part of the future bridge operation process.

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