Application and Research of Health Monitoring System of Xiangshan Port Bridge

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Abstract. The core of bridge development in China is from construction to maintenance. Therefore, the structural health monitoring system (SHMS) which can monitor and evaluate the bridge structure condition in real time has attracted wide attention. In this paper, according to the management and maintenance requirements of Xiangshan Port Bridge, the health monitoring system is designed, including sensor subsystem, data acquisition and transmission subsystem, integrated monitoring and evaluation subsystem. Afterwards, the SHMS set up, including the installation of sensors, debugging of system, development of Web User Interface and other work. After trial operation, the results show that the SHM of Xiangshan Port Bridge runs smoothly and can monitor changes and trends of state parameters of bridge structure in real time and dynamically, which provides a scientific basis for the evaluation of bridge structure state and facilitates overall lifetime management of the bridge.

Keywords. Bridge engineering, cable-stayed bridge, SHM.

1. Introduction
In recent years, some key problems and diseases have appeared during the service period of Bridges in China. Some Bridges even have sudden catastrophic events under the traffic load or environment load, which has caused a bad social impact [1-5]. At the same time, the Ministry of Transport in the “13th Five-Year” Highway Maintenance Management Development Outline clearly pointed out that “to strengthen the health monitoring and dynamic operation supervision of the long bridge and tunnel”, which indicates that the focus of China’s bridge industry from “construction “ to “construction and maintenance”. Therefore, people pay more attention to the structural health monitoring system, which can monitor the bridge structure status in real time and predict it comprehensively.

Since the 1980s, experts in the abroad explored and studied the structural health monitoring system. SHMS have been installed on many bridges, such as continuous steel box girder bridge in Foyle (UK), cable-stayed bridge in Faroe (Denmark), Vincent Thomas suspension bridge in USA, Halkis bridge in Greece, Colle Isarco Viaduct concrete continuous girder bridge in Italy, Akashi-Kaiko bridge in Japan [1-5].

Tsing Ma Bridge and Ting Kan Bridge were the first in China to set up Structure Health Monitoring (SHM) system to dynamically monitor the state of bridge structure [1]. In China, since the 21st century, a structural health monitoring system was set up on several bridges, including the Jiangyin Yangtze River Bridge [6], the Dafosi Yangtze River Bridge [7], the Nanjing Yangtze River Bridge [8], the Runyang Yangtze River Bridge [9], the Jinyue Bridge [2], the Sutong Yangtze River Bridge [10], the Hutong Yangtze River Bridge [11] and so on. Thousands of sensors installed on each bridge to
monitor the external environment, structural deformation, structural stress, load action and other information of the bridge.

As an integral part of Yongzhou-Dongguan expressway in Ningbo, Xiangshan Port Bridge connects the north and south sides of Xiangshan Bay, providing great convenience for residents’ life and economic development in both places. The bridge is a two-way four-lane bridge with a design speed of 100 km/h. The main bridge is a double-tower and double-cable surface continuous steel box girder cable-stayed bridge with a span arrangement of (82+262+688+262+82) m and a total length of 1376 m.

2. System Design
Under the background of building a smart city, the SHMS of Xiangshan Port Bridge is based on the requirements of operation, maintenance, management and maintenance, with intelligent automatic monitoring as the purpose, to comprehensively evaluate the structure state of the bridge, and provide basis and suggestions for the maintenance and repair of the bridge.

The health monitoring system of Xiangshan Port Bridge consists of four subsystems, namely sensor subsystem, data acquisition and transmission subsystem, data storage and management subsystem and information center subsystem.

2.1. Sensor Subsystem
According to Technical Regulations for Highway and Bridge Structure Safety Monitoring System (JT/T 1037-2016), combined with theoretical calculation results and bridge detection reports over the years, all kinds of sensors are installed throughout the bridge to monitor the changes of bridge parameters in real time from three aspects, including load and environment, structural global response and structural local response. Table 1 is the specific monitoring parameters and monitoring sensors, and figure 1 is the sensor layout.

![Figure 1. Elevation drawing of sensor layout of Xiangshan Port Bridge (unit: cm).](image)

2.2. Data Acquisition and Transmission Subsystem
Two on-site acquisition centers are set up in the system, and each sensor is connected to the acquisition equipment of the acquisition center nearby through cables or optical cables. Acquisition equipment includes distributed fiber strain analyzer, fiber bragg grating (FBG) analyzer, NI data acquisition instrument, dynamic weighing instrument, etc. All the equipment in the acquisition center are advanced products in the industry, with good stability, reliability and durability. In addition, a collection and transmission control software is developed, which convert the analog signal from the sensor into the digital signal, namely “analog-to-digital conversion” (A/D conversion). Then the data
is transmitted through the network to a server in the bridge management center. Finally, the local storage, processing and control functions of data is implemented.

### Table 1. Monitoring parameters in Xiangshan Port Bridge.

| Category                     | Major parameter                                                                 | Sensor                        |
|------------------------------|---------------------------------------------------------------------------------|-------------------------------|
| Load and environment         |                                                                                 |                               |
| Vehicle load                 | Model, axle number, axle weight, speed, total vehicle weight, etc.               | Weight-in-motion              |
| Ship collision               | Pier acceleration                                                               | Seismograph                   |
| Wind speed and direction     | Bridge floor                                                                    | Anemometer                    |
|                              | Tower top                                                                       |                               |
|                              | Internal and external ambient temperature of box girder                           |                               |
| Temperature                  | Temperature of steel structure                                                   | Thermometer                   |
| Humidity                     | Humidity inside the box girder                                                   | FBG temperature sensor        |
|                              | Vertical vibration acceleration of main girder                                   | Hygrometer                    |
|                              | Transverse vibration acceleration of main girder                                 |                               |
| Vibration                    | Longitudinal vibration acceleration of main girder                               | Accelerometer                 |
|                              | Acceleration of horizontal vibration in both directions at the top of the tower  | Deflectometer                 |
| Structural global response   | Transverse deformation of main girder                                            | GNSS                          |
|                              | Longitudinal deformation of main girder                                          | Inclinometer                  |
| Deformation                  | Deviation of tower top                                                           |                               |
| Displacement                 | Longitudinal displacement of girder end                                          | Displacement meter            |
| Structural local response    | Key section strain of main girder                                                | FBG strain sensor             |
| Strain                       | Overall strain of main girder                                                    | distributed fiber sensor      |
| Cable tension                | Stay cable                                                                      | Accelerometer of cable        |

### 2.3. Data Storage and Management Subsystem

The data storage and management subsystem can be referred to as the central database subsystem, which mainly includes the computer equipment of the bridge management center and the corresponding database management and interface software. It is not only the “data information heart” of the bridge management center, but also the core of bridge information and data management. The main function is to manage and store the whole life static data and dynamic monitoring data of the whole monitoring system.

Static data information includes bridge structure information, bridge geographical location, all software and hardware technical data, parameters and pictures of the monitoring system, as well as all kinds of monitoring data file information of the monitoring system and operator permission information, etc.

Dynamic monitoring data refers to the original data of structural monitoring collected by the system in real time, including current data and historical data. There are two main methods to manage dynamic data in the SHMS. One is to directly store and manage the original monitoring data into the database table; the other is to save the original monitoring data at the acquisition equipment into a common file format (such as text format) that can be recognized by subsequent analysis software, and then download these original data files to the center server. It should be noted that the database only keeps the path information of these data files at the server. The database module belongs to a
supporting module in the SHMS. It mainly runs in the background and provides data support services for other subsystems.

2.4. Information Center Subsystem
Following the design principle of “brief introduction, clear hierarchy, complete functions, easy operation and reasonable layout”, the information center subsystem has the following functions: bridge data information query, data query and analysis, comprehensive alarm, evaluation and report, etc. The bridge information query function mainly includes the bridge static data information, namely the bridge structure information, the bridge geographical location, the monitoring system data, etc. The data query and analysis function can query real-time monitoring data and historical monitoring data, and make comparative analysis and correlation analysis on the data according to user requirements. The comprehensive alarm function sets the warning thresholds of different monitoring category according to the Standards for setting the warning threshold of long-span Bridge Structure Health Monitoring System (T/CECS 529-2018), and divides them into four levels of I–IV, which is shown in table 2. The evaluation and report function provides the application program call interface for viewing and managing reports, calls the report management module, realizes the presentation of various processing and analysis results, and evaluates the state of the bridge structure.

| Warning Level | Description | Color |
|---------------|-------------|-------|
| I             | Especially serious | Red   |
| II            | Serious      | Orange|
| III           | A little bit serious | Yellow|
| IV            | General      | Blue  |

Health monitoring system integration of Xiangshan Port Bridge is shown in figure 2.

Figure 2. Health monitoring system integration diagram of Xiangshan Port Bridge.

3. Data Analysis

3.1. Data Integrity
The data of each sensor for one month was viewed from the system platform, and the results showed that the data integrity was good, which further indicated that the subsystems including data acquisition, data transmission and data storage were running well. Due to the large number of sensors, only figures 3–4 are given here, and the rest is not repeated here.
3.2. Data Rationality

According to the different monitoring parameters of various sensors, the rationality of the data can be judged by different standards. The rationality analysis of several sets of data is given below.

The variation trend and range of cable tension in symmetrical position in cable-stayed bridge should be consistent. Figure 5 is the distribution diagram of the cable tension monitoring points of the bridge, and the cable tension of symmetrical cables in the same period are randomly selected for comparison, as shown in figure 6. The variation trend and range of cable forces of C02 and C16 are almost the same, so are C07 and C14.

By comparing the atmospheric temperature with the temperature measured at the mid-span of the steel box girder (figure 7), it can be seen that the change trend of the two is consistent. Since it takes a certain time for the temperature transfer from the atmosphere to the box girder, the temperature change in the steel box girder lags behind the atmospheric temperature, which is in line with the actual situation.
The longitudinal displacement of girder end varies with the temperature. For B04-1 and B04-2 that are the measurement points of longitudinal displacement at the beam end and B09-1 that is the measurement points of structural temperature, a day’s data of them are randomly selected for comparison, as shown in the figure 8. It can be seen that the variation trend of beam end displacement in a day is consistent with the variation trend of structure temperature, and the data is reasonable.

![Figure 8](image-url)

**Figure 8.** The contrast of the longitudinal displacement of girder end and structure temperature in a day.

4. Conclusions
In general, during the trial operation, the SHMS of Xiangshan Port Bridge can run normally and stably, and the monitoring data has good integrity and rationality. Most functions of the system can meet the expected requirements, some functions have defects or deficiencies, which need to be further improved. Suggestions for improvement are as follows:

- Enhance data filtering performance, identify and eliminate useless data from large amounts of data;
- The relationship between all kinds of data and the state of bridge structure need to be explored deeply;
- Based on the existing system to accumulate bridge data, the function of bridge structure state trend prediction is gradually developed.

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