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The Development of a Proper Laser Displacement Monitoring System for Medium and Short Span Bridges

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Abstract: The Health Monitoring System (HMS) for a Medium and Short Span (MSS) bridge is different to one for a long span bridge, because of factors such assize, scale and importance. Therefore a proper HMS needs to be developed to meet the economic and applicability requirements of the large number of MSS bridges. Approximately 90 % of existing bridges in China are categorized as MSS bridges and most are beginning to deteriorate. Furthermore, there is not a suitable HMS that can assess the condition of the bridge in accordance with a growth market where traffic volumes are likely to increase. Indeed, the artificial patrolling system currently in use is unable to monitor bridges in the long-term and highlight problems within a sufficient time scale. Having discussed the necessity of a HMS for MSS bridges, this paper proposes a suitable system that uses displacement monitoring in addition to the necessary precision. Displacement was chosen as the main monitoring indicator for intuitive, convenient and direct viewing, as its critical characteristic is that it is both economical and straightforward to use. Specific details regarding the laser displacement sensor and the development of a wireless data acquisition and transmission system are also provided. The reliability of the displacement monitoring sensor and data processing system is confirmed through different stages of an installation test. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Laser displacement sensor, Displacement monitoring system, Medium and short span bridge, Long span bridge, Remote monitoring and control, Warning index.

1. Introduction

It is well known that China is a country with many bridges, especially long-span bridges. By the end of 2012, there were more than 713,400 bridges that were 3662.78 km in length; moreover, over 90 % of these are MSS bridges. These MSS bridges consist of approximately 70 % t-beam and hollow slab bridges, 10 % concrete or masonry arch bridges and 20 % of other types of bridge. Furthermore, 40 % of these bridges have already been in service for more than 20 years [1]. The proportion of the various types of bridges is generally the same in other countries. For example, in the UK and Germany even though the life expectancy of a bridge is 75 years, the actual average life is approximately 40 years [2, 3]. Therefore, it can be predicted that in the next 10 to 20 years, there will be a large number of bridges deteriorating in China. If this phenomenon is uncontrolled, most of the bridges will be unusable long before their expected life span. At present, according to a survey, out of all the bridges that have already been in service for more than 20 years, 30 % are classified as grade three of four [4, 5].

However, the standard bridge design in China is different to that of developed countries, as its bridges are subjected to loads that are greater than those set out in the specification. Both poor construction quality and weak maintenance have contributed to a situation where the aging of bridges is more serious in China than it is in foreign countries. In addition, because of the lack of maintenance and management, the safety factors of MSS bridges are less monitored than those of long span bridges.

With regard to bridge maintenance and management, due to the complexity of particularly large long-span bridges and the associated numerous monitoring factors, the initial investment and operation costs are very expensive. For example, a quotation running into millions of RMB for a health monitoring system of along span bridge is not unusual, although they would usually cost hundreds of thousands of RMB. For example, the health monitoring system for one bridge located in the Zhejiang province, cost more than 30 million RMB [1, 6, 7].

For the vast majority of short and medium span bridges, due to their large number and the fact they are widely distributed, most owners or management departments of the bridges cannot fund the expensive maintenance and monitoring costs. Moreover, departments do not pay enough attention to these small and medium-sized bridges and there are not sufficient numbers of technical workers allocated to them [3, 8]. For this reason over 90 % of these bridges (i.e. with spans smaller than 100 m) in China do not have a monitoring system installed upon them. However, accidents regularly occur on these bridges, and traffic is always delayed even though the major long span bridges are still in service.

At present, surveys of MSS bridges are always conducted using the conventional manual method, which includes regular testing and routine inspection. These passive detection methods, which are limited by man-made factors, are only useful for obvious and visible defects. Furthermore, it is difficult to determine the bridge's overall health status and how this will develop over time. Load testing, which is recognized as an effective detection method, is expensive and will impede traffic, thereby affecting the bridge's normal service. Additionally, load testing may lead to the bridge becoming damaged; therefore, unless there are very special circumstances, this method is generally not adopted. Regular inspections can only determine the bridge's health status at the time and evaluate the rest of its service life; however they cannot guarantee its future safety with any certainty.

In China, it was detected that for some bridges located in the mountains or foothills there may be major hidden dangers, for which it was necessary to take corresponding measures in order to ensure the safety of the bridge's structure. However, there are several stages from the discovery of such a hidden danger to the completion of any associated repairs; these include, research, a maintenance plan, reporting to the relevant authorities and gaining approval for the repairs, all of which can take months or even more than a year. During this period, in order to ensure the safety of the bridge, which can still be in service despite the defects, it is necessary to monitor the ongoing condition of the bridge with more regular inspections. However, due to the fact that these faulty bridges are located in the mountains or in a hilly area with many canyons, it is very difficult and costly to carry out these inspections. Therefore, although they are high quality MSS bridges, it is still necessary to create or install a remote automatic monitoring system both before and after the hidden danger was found, in order to ascertain in real-time the bridge's condition and carry out an analysis and early warning assessment.

More than 90 % of the bridges in China are short and medium span bridges, and as the amount of time these bridges are in service grows, an increasing number of them will begin to deteriorate to a certain degree. If the department in charge of bridge management continues to only rely on a hand-operated detection means to monitor the condition of the bridge's structure, the frequency of the manual detection will need to increase, which will lead to the associated costs (including lab our and materials) increasing significantly. In order to ensure that those particular bridges that are found to be unsafe are usable before effective maintenance measures are taken, it is necessary to create practical and economic procedures for these bridges' monitoring systems.

At present, health monitors for a bridge's structure, particularly for a large-span bridge, are common and many different types of equipment and technologies have been invented and adopted. The levels of investment and societal demand for large span bridges are always are significant, and they have many associated difficulties due to their complex structure, design and construction. Because of this they are often the focus of the public's attention, which results in the negligence of the less high profile MSS bridges on highways, state highways, and country roads. In China, more than 90 % of bridges are MSS bridges and to guarantee the safety and efficient operation of these bridges is to also ensure the key points of the land transport network, which cannot be ignored, are maintained.

In recent years, as more short span concrete girder bridges appeared, different levels of deterioration have led to serious accidents and even the bridge collapsing. Therefore management and technologists are beginning to pay more attention to the operational security of these bridges, and they realize that it is difficult to monitor the bridge's safety condition through artificial, regular detection. This highlights the obvious problem of making judgments with subjective information, especially as is normally expensive to detect faults in a bridge. Therefore, it is necessary to establish an economical and practical procedure for a health monitoring system for these

MSS bridges. However, it is unacceptable to simply copy the monitoring system of a large span bridge, because it is a different type of bridge and the costs of the requisite special indicators are also different. Thus an alternative method for MSS bridges is required and the economic cost of the appropriate monitoring system needs to be addressed, including factors such as hardware investment, construction, operations and management and maintenance.

2. The Characteristics and Requirements of a MSS Bridge Monitoring System

In order to develop a proper targeted monitoring system for MSS bridges, it is necessary to understand the differences between the monitoring system characteristics of a MSS bridge and those of a long-span bridge. An analysis of the current bridge monitoring systems reveals that they have the following common features:

1) The bridge monitoring system consists of a hardware and software systems. The hardware system generally consists of a sensor system, data acquisition and transmission system and data analysis and processing system; the software system implements the status identification and safety assessment for the structures.

2) The condition of the bridge's structure is recorded via the placed sensors; these sensors pay great attention to the environmental conditions of the bridge, such as the temperature, wind, and traffic load.

3) Thanks to the development of test and communication technologies, the monitoring system can collect the information more accurately and completely, and makes use of the large capacity of the network sharing system.

4) Up until now, more attention was paid to research on, and practical guidance for, monitoring systems for long span bridges, and those for MSS bridges were ignored.

As there are a large number of MSS bridges that are widely distributed, the existing bridge monitoring systems are not suitable. In particular, the management department cannot afford the high cost of monitoring these bridges. Therefore, it is necessary to resolve the cost issues of the monitoring system for MSS bridges, including hardware investment, construction, operation, maintenance and management. The following issues need to be resolved:

- First, as there are different monitoring goals for large-span bridges, it is necessary to select the unique technical parameters that relate to the medium and small span concrete girder bridge's characteristics.
- Secondly, the high cost of health monitoring should be reduced by the use of economical and suitable sensors, which cover the application range in 90 % of China's bridges.
- Third, uniform monitoring and assessment criteria should be created in order to facilitate management and decision making.

Therefore, proper sensors, suitability and economic requirements, are the key issues in promoting a monitoring system that can be applied to the larger number of MSS bridges. The requisite monitoring targets or parameters should be completely representative, and these will directly relate to the budget for the development of equipment.

Consequently, based on the above analysis, the monitoring system for MSS bridges needs to focus on the results, and not on the causes of the problem. Specifically, it is simply necessary to consider the quantitative index, and avoid analyzing various complex factors, including the environment and traffic loads. For MSS bridges, the cross section deflection of a bridge is the most important indicator. At present, in China, the hollow slab bridge is overwhelmingly the most common in use. Due to traffic overload, damage of the hinge joints and poor lagging, these bridges have a number of obvious cracks. This has led to a vicious cycle of lower structural rigidity. Correspondingly, as the stress or strains increase so do the width of the cracks and they can all be directly reflected in the deflection.

Therefore, in light of the monitoring indicators for MSS bridges, the deflection is determined to be the first index. Only when the condition allows, the stress/strain and crack width, and even the vibration frequency of a bridge, can be monitored to improve the accuracy of the monitoring and overall judgment.

In accordance with the above discussion, this paper investigates the hardware and software for monitoring MSS bridges separately. It was found during the study that three aspects of a combined monitoring system with hardware and software must be resolved: the stability of various types of sensors and their replace ability; the acquisition and transmission of intelligent monitoring data; and the rational display and analysis of monitoring data.

2.1. Sensor Stability and Replace Ability

At present, the artificial inspecting and load testing of a bridge always uses the conventional or special sensors in order to collect various data regarding structural response; the test time is short and sometimes only a few days in length [9, 10]. Therefore, if the sensors can be guaranteed to be stable during this period, more long-term stability is not required. However, for a structural HMS, the sensors need to be installed on a bridge for many years; thus the sensors should be stable during this long-term monitoring period in order to avoid problems such as data drift from a strain gauge [11, 12]. In addition, the related monitoring equipment should be replaceable when it gets damaged or needs to be updated. Therefore, as the embedded sensor is unsuitable for a HMS, a new and proper displacement sensor was designed and developed for a MSS bridge; this sensor has long enough life, can be replaced easily, and keep data continuously even if the monitoring of the data was interrupted.

2.2. Reasonable Acquisition and Transmission of Monitoring Data

The existing structural HMS of a large-scale bridge generally has a high sampling frequency for parameters, and large amounts of data are collected; this leads to a heavy subsequent data processing analysis workload [2, 12]. Therefore, a key problem is how to guarantee that the accurate condition of the structure is monitored in time with a rational sampling frequency in order to decrease the data size. In this paper, the suitable acquisition model was designed with a frequency that was appropriate to the probability of the service load and overload. In addition, the issue of how to accurately, smoothly and economically transmit the data to the control center is important and needs to be considered and resolved.

2.3. Reasonable Display and Analysis of Monitoring Data

According to the actual needs of owners or managers, the data display and analysis processing system (software) should be set up following these principles: the interface is simple and clear; the layer structure is distinct; and it is easy to operate[2, 13]. In particular, the analysis of the post-processing stage needs to solve the issues of how to establish a safety early-warning subsystem and improve its accuracy and how to make use of the analysis results so that a manager can take decisions.

3. The Monitoring Factor and Sensor Design

3.1. The Monitoring Factor Selection

In order to select the monitoring target and factors based on a full investigation and analysis, and considering the fact they were working with medium-and-short span bridges, the authors chose a method concerned with the results and not the cause. That is to say, it only considers quantitative monitoring indicators and avoids an analysis of the environmental impacts, the traffic load and other complex combinations of factors.

For medium-and-short span bridges, the damage cause do the bridge is relatively simple and always consists of a large deformation. Therefore, the deformation of the bridge is one of the most critical indicators. In China, most MSS bridges are of the hollow slab beam type and serious cracks to the beam are caused by damage to the hinged joints, an overload of traffic, repairs being delayed and weak management. This leads to a vicious circle of lower structural rigidity. All the causes above will increase the stress/strain, or even lead to increased crack widths, which are also directly reflected in the increased deformation of a bridge. Therefore, the monitoring indicators of the small and medium span bridge deflection index are those that will lead to the goal being achieved. If the conditions permit, the precision of the monitoring can be improved by looking closely at the stress/strain of the key sections, the crack width, or even the natural frequency of the structure, all of which will lead to a more comprehensive judgment.

A 20 cm range is sufficient for economical and applicable monitoring equipment that is analyzing the structure’s deformation, and taking into account the small range of MSS bridges. It is necessary to take a positive and negative 10 cm deformation as the monitoring range and take into account factors such as the environmental impact and installation effect on site. Furthermore, precision with regard to millimeters is required; therefore, for a long-term monitoring sensor on site, the precision grade in millimeters with a measuring range within 10 cm is definite. Based on these requirements and the comparison analysis of the various types of equipment, the research team has developed a laser sensor. This sensor can be a single point with collector or multi-point summary and is a centralized data-acquisition system for an entire bridge. Currently, the price for each sensor is about 4,000 RMB, including data acquisition and transmission.

3.2. The Monitoring Working Principle and Design

The laser displacement sensors developed in this paper are based on the laser measuring method of deflection monitoring of bridges with the RS-485 data bus (See Figs. 1 and 2). In fact, the laser sensor is no different to other normal laser displacement sensors, which all have two parts: a laser emitter and laser receiver. Because the laser has many advantages with regard to directional property and high suitability both on site and in sunlight, this ensures the sensor has good sensitivity as a benchmark to measure the deflection of a bridge [14].

The basic principle is when bridges are subject to traffic load, the laser receives information from a processor fixed on the girder and will be subject to the same deformation as the girders, while the laser emitter is motionless relative to the piers or foundation. The image of the moving laser target is displayed on the screen of the receiver processor with a photosensitive sensor, and the laser displacement is correspondingly converted into signal data by online data processing. Subsequently, the real-time deformation is transmitted through the RS485 bus to the transfer device, which will send the data wirelessly to the remote center.

The bridge deflection monitoring system (DMS) consists of several sets of deflection monitors (DM), a transfer device and remote control center. Each deflection monitor consists of a laser emitter and a laser receiver processor. There are two sets of DM for each span while the transfer device can service many spans. When a receiver processor obtains a signal from the remote control center to measure the deformation, it will supply 5 V direct current to the laser emitter so that is can send the laser.

Each DM connects with the transfer device via the RS485 bus. The laser emitter should be installed with a bracket on a relatively fixed object, such as a pier or pile cap, which is adjacent to the girders that are being monitored. The laser receiver should be installed underneath the bridge, where the deflection is possibly the largest or is the most unfavorable. The laser receiver processor should face the emitter and have enough range to allow the laser to move on its screen.

On the RS-485bus, each laser receiver processor works in a polling mode, which means the processor only responds when it receives the command from the upper machine (the transfer device) and outputs bytes of data as signs of displacement. After the transfer device receives an answer from the processor, the next monitoring unit begins to work, and the process continues in cycles. The transfer device sends an instruction that is made up of four bytes; the format is: ** @@ ## ##; where '**' is the processor ID of the laser receiver, the '@@' is the displacement and four '#' is the CRC16 check code. Each byte is sent continuously and each batch over an interval of 50 ms. The laser receiver processor response instruction format is: ** @@ $ $ ... ... $ $ ## ##; where '**' is the laser receive processor ID, the '@@' is the command codes, the '$$' refers to the monitoring result and the four '#' sign represents the CRC16 check code. The bytes are sent continuously.

In Fig. 3, the layout of the integration is shown with a control box. The data acquisition-transmission modules were simply integrated into the control box. In fact, Fig. 2 is also the equipment wiring diagram for installing this system into each span of the case study bridge.

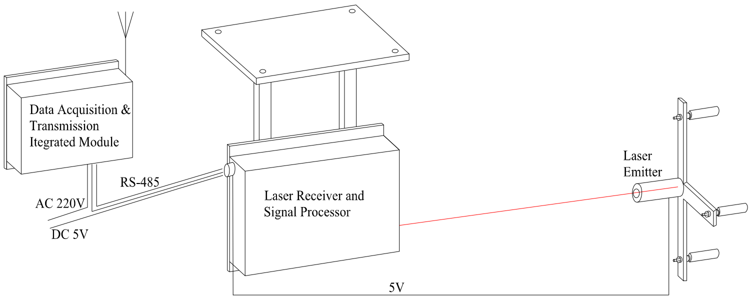

Fig. 1. The laser sensor functional diagram.

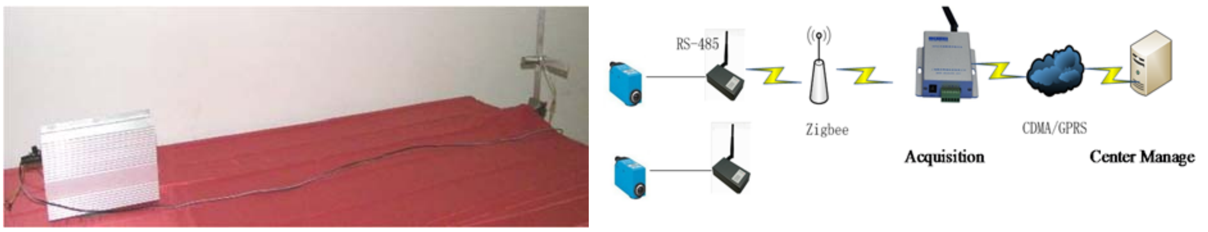

Fig. 2. A picture of the sensor's prototype and a diagram of the data acquisition-transmission module.

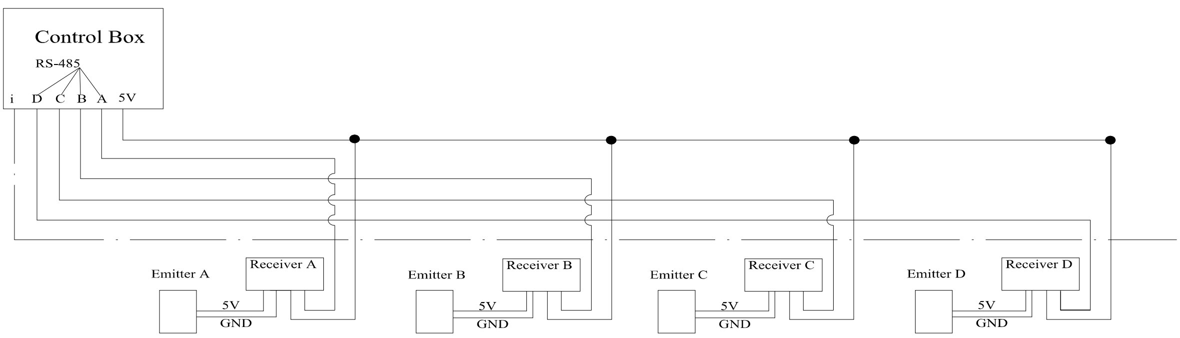

Fig. 3. The equipment wiring diagram for one span.

3.3. Calibration and Test on Site

The basic properties of the sensor should be known before they are used on site in order to ensure its accuracy and verify the installation process; therefore, it is necessary to calibrate the sensor. However, because the laser displacement sensor belongs to a non-contact measurement instrument with a high precision, the calibration process is difficult. According to a height indicator, the proven precision is 0.3 mm with a measuring range of 100 mm (See Fig. 4). Moreover, according to the possible stage of deformation of a medium and short bridge, this precision satisfies the monitoring requirement [16].

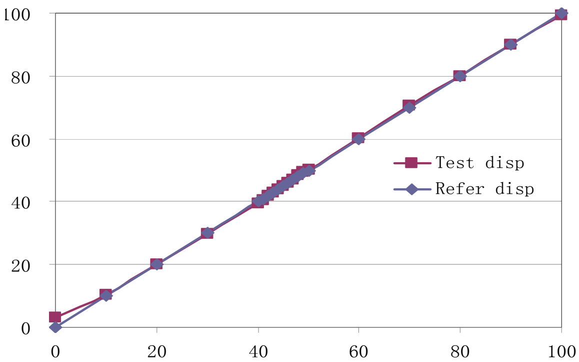

Fig. 4. The instrument calibration curve with an altimeter (Unit: mm).

Having completed the prototype, the researchers tested it twice. The first time, two sets of laser sensors with wireless data transport modules were installed on a bridge in the campus of the Zhejiang Institute of Communication in the strong sunlight. The suitability of the location of the emitter and receiver was checked (See Fig. 5); however, the alignment of the laser proved difficult and fine turning was required in order to get it to hit the target.

Fig. 5. A test on the deck of bridge.

On the second occasion, having optimized the stability of the laser emitter, the alternate set was installed under the same bridge; the installation simulated the actual construction stages by using a bridge inspection vehicle (See Fig. 6).

Fig. 6. A test under the bridge.

4. The Monitoring and Warning System

It is necessary to have a corresponding data operation platform for management, as well as the appropriate hardware, in order to produce a complete and successful monitoring system; sometimes the success of the monitoring system depends on the remote operation platform [17, 18]. The research team designed and developed a set of remote monitoring platforms at the same time as they developed the laser displacement sensor; the platforms were developed taking into account the monitoring displacement parameters and the characteristics of the bridge. Thereby an integrated system was formed, including measuring, data transmission, remote control and management.

The possible maximum deflection of MSS bridge is definite [5, 19]. A simple supporting girder can be used as an example; if the pier or pile cap was assumed as a fixed benchmark, the bridge deflection under vehicle load can be divided into an allowing deflection under normal service load or an irregular deflection under overload/abnormal load. If all the peak deflection data are connected into a curve, it is possible to define them approximately as the long-term service action effect and short-term abnormal action effect. These two envelope curves are the basis of creating a warning system.

Meanwhile, there is another important factor, the service life, which is related to time and should be considered. The structural function deterioration or loss will gradually increase the long-term deflection, and this phenomenon will be shown through the deflection envelope curves, as the peak data will increase with time. The acquisition frequency is directly related to the accuracy of the warning value. Therefore, for a monitoring and control platform, there are three indexes of the different level warning values for the managers to analyze and assess the health condition of the bridge.

For example, for a new bridge, the usual permission deflection under permitted design vehicles, including a heavy vehicle load, can be calculated through analysis, which can be defined as a common green warning value or the first-level warning value. For an existing bridge, after being in service for several years, traffic overload is common – particularly in China. The existing time and defects lead to the deflection increasing; therefore, the first-level warning value should be equal to or greater than this green warning value. When the bridge is subjected to overload, the deflection should be greater than the first level; this is the second-level warning value which the authors define as a yellow warning value. The top-level warning value, or the ultimate red warning value, can be drawn through two methods: one is through the envelope curve of the abnormal deflection peak points; another is through the frequency or interval of the abnormal deflection points (See Fig. 7).

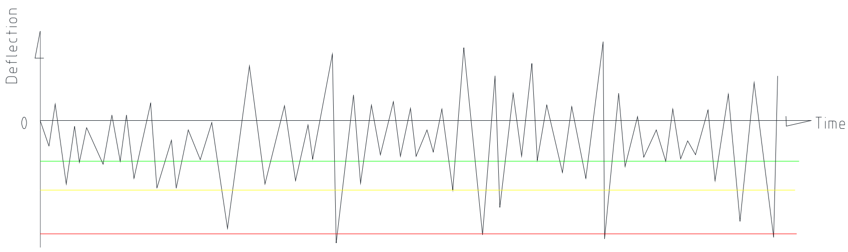

Fig. 7. The theoretical excepted relationship between the three indexes of warning value.

Based on the above analysis, the monitoring software platform should include the following features:

- The real-time data form should display the current and recent acquisitions; the corresponding data curve can be obtained and shown on the screen and output.
- For each specific bridge, the platform can set respectively a one-time yellow warning value and an adjustable red warning value for more than one time; these warnings can be displayed and compared with the real-time data in order to simultaneously judge the developing trend of data.
- The software can connect the peak data automatically according to the time interval in order to show the long-term trends of displacement; according to the time interval, the peak data that goes beyond the warning peak load can be automatically connected to show the worst state as a long-term trend.
- To be able to pick on the screen or select the sensor number through the interface (one or more), and synchronously display the selected sensor real-time curve according to the monitoring location.
- With regard to the time interval, the real time curve can be displayed in minutes, hours, days or months, all of which can be chosen from the full-term curve.

5. Applications in a Case Study Project

To prove the reliability and precision of the laser sensor, a case study bridge, which is located in Qingtian, Lishui City, Zhejiang Province, was chosen and this equipment was installed upon it. This 1913.18 m long bridge was opened in 1995 and consists of 120 spans. Each 16 m long span is a simple supported girder bridge, which consists of ten hollow prestressed-concrete-plate beams. According to inspection result of December 2009 from the Code for Maintenance of Highway Bridges and Culvers (JTG H11-2004), the bridge is graded level III with its overall engineering in a good condition. However, some elements need minor repairs and maintenance. The bridge's condition is good and the authors were satisfied that it fitted the requirements for installing the inspecting sensors.

There was another reason this bridge was chosen for the installation of the monitoring system. Due to the rapid growth of traffic, the government of Qingtian County decided to direct some vehicles to the case study bridge. In order to ensure vehicle safety and an orderly flow of traffic, a set of traffic lights was set up on the bridge. However, when the bridge is in normal service, the bridge management department gets a lot of feedback from drivers, for example, it is obvious when the bridge vibrates as drivers brake or restart their vehicles. Therefore, in order to ascertain the actual condition of the bridge and guarantee its safety, the bridge was chosen as an example of a typical beam bridge on which the HMS could be installed for real-time monitoring.

Two spans were chosen on which to install the sensors. One was just next to the interchange span; another span was several spans in interval from the first. For each span, four sets of sensors were installed: three group sensors were installed along the longitudinal direction; the laser receivers were installed in the mid-span section; and the laser generators were installed on the pier capping beam. Another set of sensors was installed on the pier capping beam along the transverse (See Figs. 8 and 9). The system integrated a data acquisition and transmission module, meaning that the remote inspection data was easily received in the office terminal.

Fig. 10 shows the partial data of the case study bridge. The deflection data displayed a good pattern with a time variation. Because the bridge was in a good state of repair, it is clear that the three warning values are at different levels.

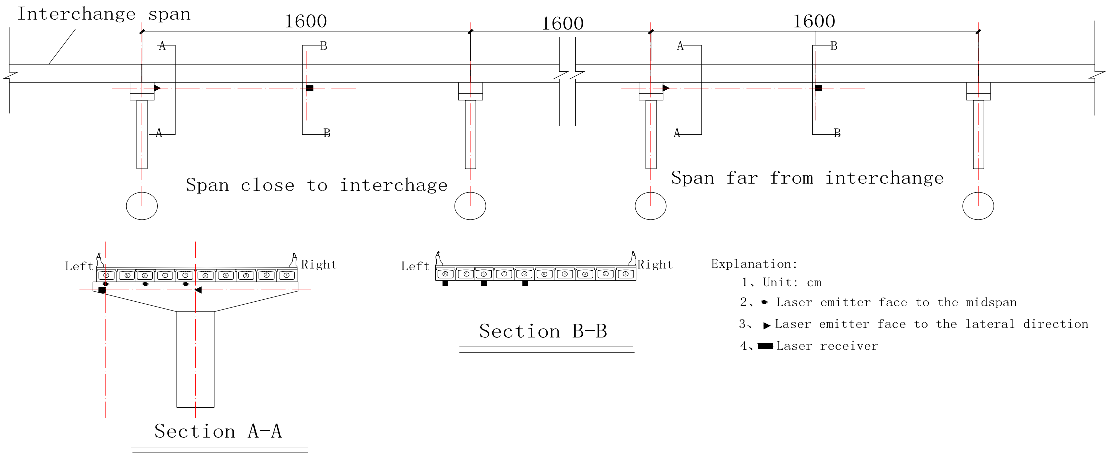

Fig. 8. The layout of laser sensors on the bridge.

Fig. 9. A photo of the bridge after all the sensors were installed.

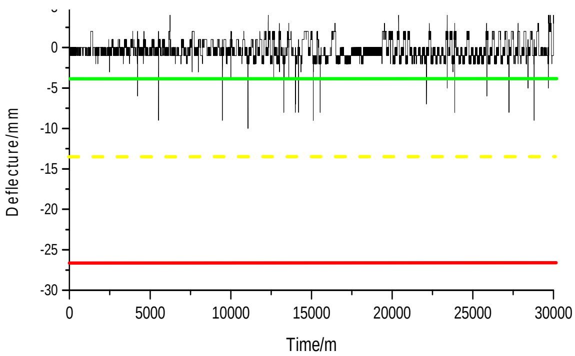

Fig. 10. No. 5 sensor's data of the case study bridge.

6. Conclusions

The monitoring of MSS bridges is necessary after they have been in service for several decades; furthermore, the monitoring system for this type of bridge is fundamentally different to that of a large-span bridge. The feasibility of using the system for a large-span bridge depends on its cost and how applicable it is to smaller bridges. The laser sensor with remote data transporting capabilities is suitable in size and can work in strong sunlight; therefore it is sufficient to fulfill the requirements of monitoring a MSS bridge. The range between -100 mm and +100 mm and its precision at these millimeters is sufficient for displaying the actual condition of these bridges. The data checking and testing at the site proved that the sensors with these indexes are inexpensive and suitable for a wide range of applications. The validity of this monitoring system will be proven once the results from the case study bridge are available. For an existing MSS bridge, there are three indexes for the three levels of warning values of the monitoring and controlling system: the theory deflection; the abnormal deflection under an overload/exceptional load; and the long-term deflection that is increased by the structural deterioration.

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