Study on Dynamic Characteristics of Train-bridge Coupling Based on Wireless Sensor Network

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Abstract

It is very important to monitor dynamic responses and health states of the bridge in time and avoid occurrence of bridge collapses accidents. The bridge span is relative large, so detected positions should be scattered, and sensors should be placed on multiple cross sections. In traditional dynamic response tests of bridges, data collection is generally based on the wired type which is deficient in inconvenient installation and wiring. Aiming at those defects, this paper applies WSN (wireless sensor networks) technologies to test dynamic responses of a bridge under train effects. The WSN is a network system formed through a wireless communication type. It could sense, collect and process information of sensed objects in a network coverage region in a collaborative manner, and could send the information to users of the network through wireless transmission. Finally, through comparing with those results of wired sensors, reliability of tested results in the paper and validity of network layout were verified.

Keywords: Dynamic responses, Bridges, Wireless sensor networks, Trains

1 Introduction

When a train passes through a bridge, the bridge will bear both the static loads generated from its weight and the moving loads of trains, as well as the inertia force caused by train vibrations. Due to the varying vibration force, the probability in fatigue damage of bridge structures is greatly increased, and strength and reliability of each part are reduced. In addition, due to bridge vibrations, running trains would generate vertical accelerations, which could reduce the running stability and safety. When the vibration frequency of a train is equal to or approaches the self-vibration frequency of a bridge, the bridge resonance would be caused and the bridge would have huge dynamic responses. As a result, the bridge structure will be damaged [1-4]. Therefore, it is very important to monitor dynamic responses and health states of the bridge in time and avoid occurrence of bridge collapses accidents [5-9].

The bridge span is relative large, so detected positions should be scattered, and sensors should be placed on multiple cross sections. In traditional dynamic response tests of bridges, data collection is generally based on the wired type which is deficient in inconvenient installation and wiring, complicated maintenance, long construction period, high construction cost, poor mobility and expansibility, and the necessity in artificial collection for all the sensor data [10]. With the development of modern testing technologies and communication technologies, a testing system based on the WSN is proposed [11-14]. The WSN is composed of a lot of cheap micro-sensor nodes distributed in the monitoring region. It is a network system formed through a wireless communication type. It could sense, collect and process information of sensed objects in a network coverage region in a collaborative manner, and could send the information to users of the network through wireless transmission. The WSN is popularized and easy to be distributed, so that it is used to take the place of a current offline periodic monitoring system, so that more important and timely information could be provided and manual labor could be maximized. In addition, it could effectively solve problems faced in use of a wired sensor system. For example, problems such as inconvenient wiring, and difficult replacement and installation of sensors could be avoided. In particular, a movable wireless sensor could avoid the problem of traffic blocking in bridge testing and save the cost. Therefore, the WSN is widely applied in health monitoring of bridges. Ji et al. [15] installed the WSN nodes on suspended cables of Yangtze River Bridge, collected the vibration information of the suspended cables by the nodes, and then sent the information to base station nodes. Vibration frequencies of the suspended cable could be obtained through analyzing data; finally, the structural health state of bridges could be known. Zhou and Li [16] studied arrangement methods of the WSN nodes and applied them to health monitoring of long-span bridges in order to obtain more structural information. Based on integration of nondestructive detection and WSN

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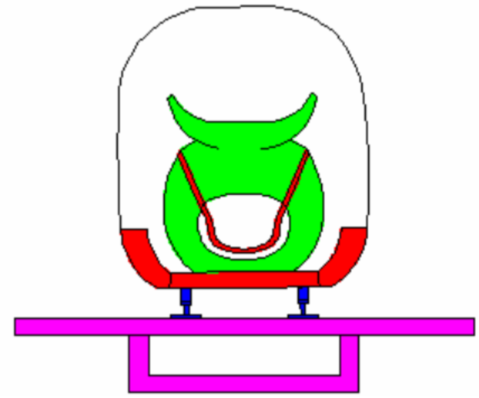
DOI: 10.3966/160792642019032002022

technologies, Xu et al. [17] designed a bridge load monitoring system based on Zigbee wireless sensor network. Yang and Liao [18] analyzed reasons why the reported wireless routing protocols could not be directly applied to the WSN of bridge health monitoring and proposed a targeted routing protocol adaptable to the application environment of the WSN of bridge health monitoring. However, these reports failed to apply the WSN to testing of bridge dynamic characteristics and only applied it to monitoring bridge structure health.

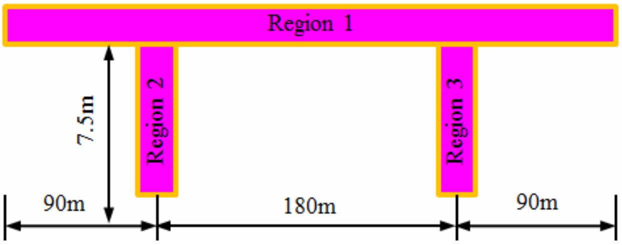
Aiming at defects in reported researches, this paper applies WSN technologies to test dynamic responses of a bridge under train effects. At present, data collection modes in the WSN mainly include WiFi, NRF903, GSM, Bluetooth, etc. They are deficient in large node power consumption, short transmission distances, difficult networking, small node capacity, etc. [19-22]. Therefore, this paper applies ZigBee technologies to collect node data in a WSN. It is advantageous in low power consumption, long transmission distance, easy networking, low cost, large network capacity, etc. [23-25]. Collected network node data was transmitted to a data server for processing and analysis by users. Through comparing with those results of wired sensors, reliability of tested results in the paper and validity of network layout were verified.

2 Testing of Bridge Dynamic Responses with Traditional Method

Figure 1(a) shows a running high-speed train on a bridge at the speed of 200km/h. Related sizes of the bridge are shown in Figure 1(b). The bridge deck is supported by a left pier and a right pier; length of left and right side spans is 90m; length of the main span is 180m; height of the piers is 7.5m. Under effects of the high-speed train, bridge bodies and piers will generate vibrations. Therefore, the bridge was divided into three testing regions. As shown in Figure 1(b), the acceleration sensor was arranged on the bridge body at an interval of 18m. 21 sensors were arranged in total. The acceleration sensor was placed on the piers at an interval of 2.5m. Three sensors were arranged in total, as shown in Figure 2(a). Due to the long bridge span, the data line would be too long if data of all the acceleration sensors was collected in a test. Meanwhile, large resistance caused by the data line would affect the tested accuracy because vibration signals of the bridge were transformed by the acceleration sensors into electric signals and were then transmitted to a data collection equipment through a data line and input into a computer, as shown in Figure 2(b). If the data line is too long, its resistance would be large, which would affect transmission of electric signals and further affect tested results. Therefore, this paper conducted 5 tests, and the tested time is 12s. In the first 3 tests, signals of 7 acceleration sensors on the bridge deck were collected each time. In the last 2 tests, signals of 3 sensors on piers were collected. In this way, vibration signals of all the acceleration sensors on bridge bodies and piers could be obtained. Through processing vibration signals, vertical vibration accelerations on each key cross section and piers of the bridge could be obtained, as shown in Figure 3.



(a) Train-bridge coupling system



(b) Related sizes of bridges

Figure 1. Related descriptions of train-bridge coupling system

(a) Layout of acceleration sensors

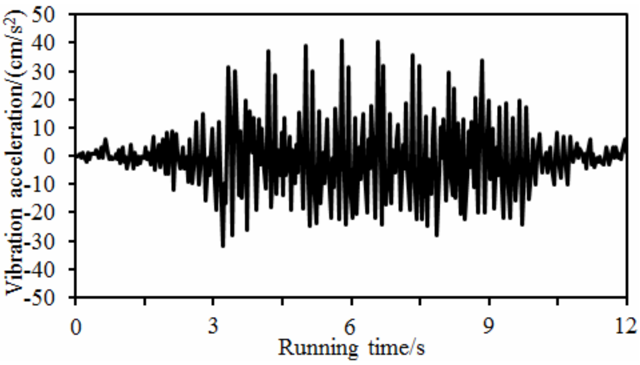
(b) Field diagram and collection equipment

Figure 2. Experimental tests on bridge dynamic responses

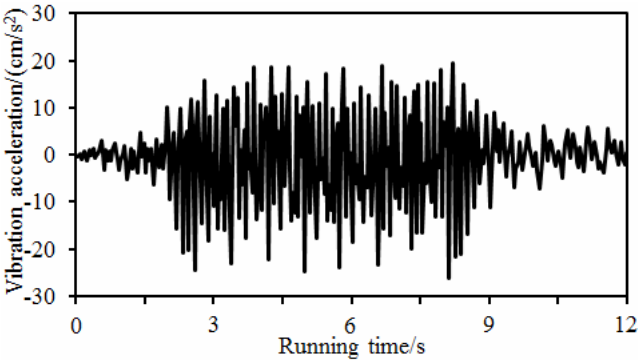
It is shown in Figure 3 that mid-span cross section and side span cross section of the bridge had the maximum vibration acceleration. The vibration acceleration on the pier cross section was obviously less than that at other positions as piers had large rigidity as a whole and would generate smaller dynamic responses under the same load excitation. It is shown in Figure 3(d), Figure 3(b) and Figure 3(a) that dynamic responses of the bridge cross section were developed backwards gradually, and the peak moment of each part in this bridge is not consistent. The reason is that the train would firstly act on the side mid-span cross section, and then acted on the 1/4 mid-span cross section and finally acted on the mid-span cross section. In addition, the vibration acceleration would be smaller on the 1/4 mid-span cross section due to the pier supporting; side span and mid-span cross sections had long spans and their bending rigidity was small as a whole, so that responses of vibration accelerations will be larger. In addition, horizontal dynamic responses of side mid-span cross sections of the bridge were extracted, as shown in Figure 4. Compared results between Figure 3 and Figure 4 prove that horizontal dynamic responses were obviously smaller than vertical dynamic responses because the excitation direction is mainly in the vertical. Therefore, this paper neglected horizontal dynamic responses during the analysis.

3 Testing of Bridge Dynamic Responses Using Wireless Sensor Network

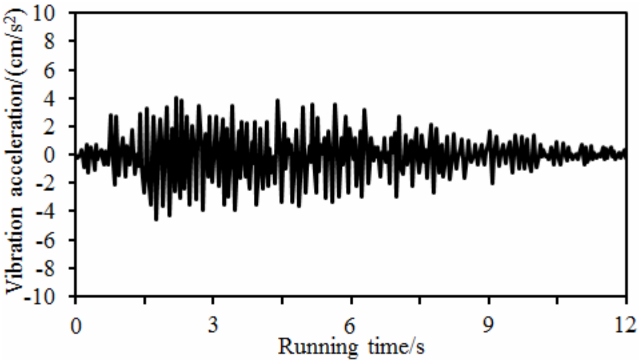
As mentioned above, dynamic responses of the bridge were tested by traditionally wired sensors. One complete testing result could be obtained after 5 repeated tests. Therefore, the tested efficiency is low and the process is inconvenient. Here, the paper thought about using a WSN to test dynamic responses of the bridge and compared the obtained results with those of wired sensors in order to verify feasibility of WSN. WSN is composed of a lot of fixed or movable sensor nodes [26-28]. It forms a wireless communication system in the form of self-organization. Different from the traditional wired communication, WSN senses, processes and transmits related environmental changes of a monitored object in the monitoring region through wireless collaboration and then reports the information to a backstage control center. WSN is featured by small size, flexible motion, low cost, self-organization, self-cure and so forth, so it could be distributed in a needed monitoring region with high density and large scale. As shown in Figure 5, WSN is widely applied to refined agriculture and intelligent traffic systems.



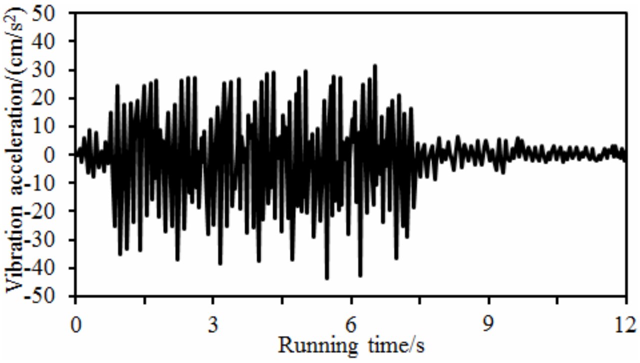
(a) Mid-span cross section



(b) 1/4 mid-span cross section



(c) Pier cross section



(d) Side mid-span cross sections

Figure 3. Vertical acceleration at each key cross section of bridges

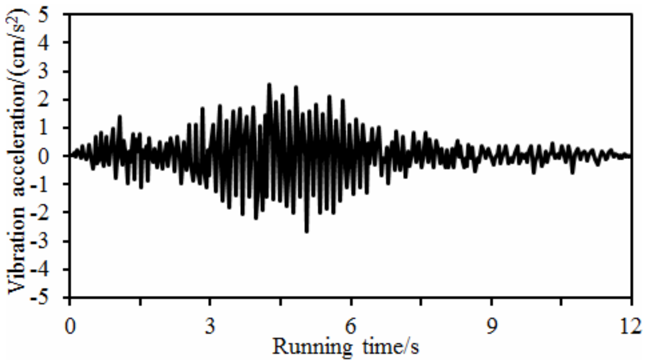


Figure 4. Horizontal acceleration of side mid-span cross sections

(a) Refined agriculture

(b) Intelligent traffic system

Figure 5. Application of wireless sensor network

In WSN, ZigBee technology is a novel wireless communication technology with a uniform technological standard distance. It mainly has 3 network topologic structures, namely star network, mesh network and cluster network, as shown in Figure 6. A network could contain 65000 nodes at most. It adopts the CSMA/CS protocol to ensure safety and reliability of communication. Therefore, it is widely applied in industrial control, intelligent medical service, smart home, security monitoring, intelligent monitoring and other fields. Through analyzing the ZigBee communication technology and combining with testing requirements for bridge dynamic responses: requirements for data transmitted by each node are not high; quantity of sensor nodes is relatively large; distribution scope is wide; power consumption of node work is low. Therefore, the optimal scheme is to take ZigBee technology as the wireless communication technology of WSN in the system.

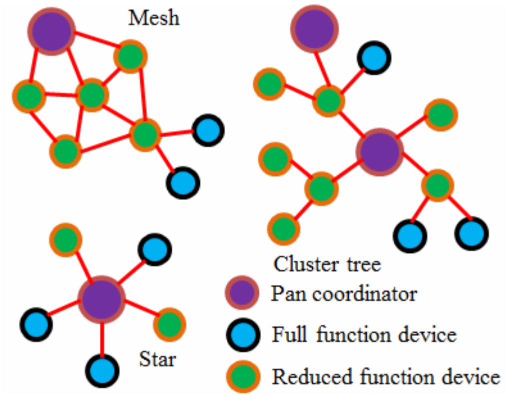


Figure 6. Network topologic structure of ZigBee technology

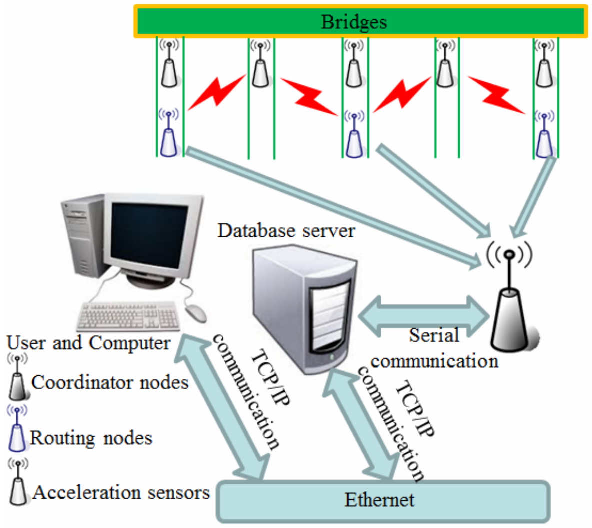
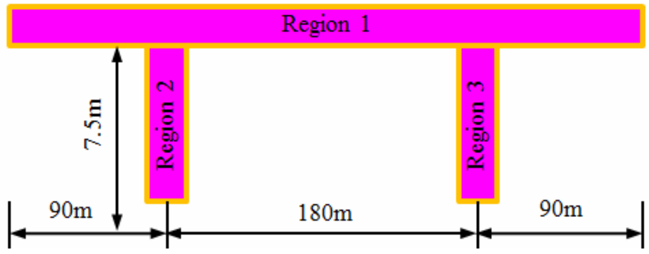


Figure 7. Testing of bridge dynamic responses using WSN

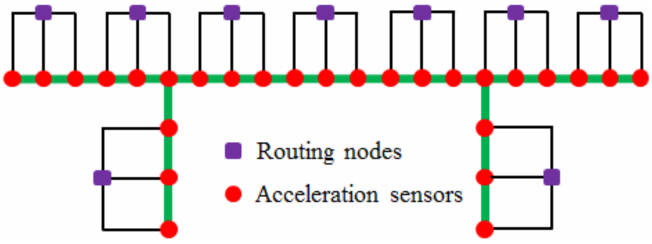
In the paper, acceleration sensors and ZigBee wireless communication protocol were used to constitute a low-layer wireless testing system. Computer language was used to compile a computer data management server based on the Windows platform and client side software. When acceleration sensors of network nodes monitor dynamic response data, they could conduct conversion, binding and layout of the data, and then the data would be multi-hop distributed to a coordinator by routing nodes. After receiving the data, the coordinator will judge whether the reception is correct according to calibration and judgment data sent by the frame format. If the reception is wrong, the coordinator will send an instruction to make the sensor nodes re-monitor and re-send data. If the reception is correct, the coordinator will send data to the computer server by a serial port connected to the upper computer for related processing. At this moment, operators can check and analyze the data through Internet access to the upper computer server. The overall structure diagram is shown in Figure 7.

It is shown in Figure 7 that wireless collection system of the dynamic response in the lower layers is based on the ZigBee wireless sensor network. It is mainly composed of 3 types of nodes: coordinator nodes, routing nodes and acceleration sensors. Acceleration sensors directly collect data of bridge dynamic responses. They are placed on bridge deck and piers. Routing nodes are mainly used for wireless relaying of sensor nodes. Therefore, it shall be placed within the farthest communication distance of a single sensor. It is best to arrange it within a common communication scope of several terminal sensors. In this way, the quantity of routing nodes can be reduced, and routing selections for each sensor node could be increased. The coordinator node is a key node in the complete wireless system, bearing construction of the complete wireless network. Its layout shall contain as many routing nodes as possible.

The bridge was divided into 3 testing regions, as shown in Figure 8(a). Piezoelectric acceleration sensors were used to test acceleration responses of bridge deck vibration. The wireless node had three channels. Each channel could be connected to 1 wireless sensor. In other words, a wireless node could collect data tested by 3 wireless sensors at the same time. A wireless emission module and a wireless receiving module were set in the node. The wireless receiving module was used to receive a collection command sent by the user. The wireless emission module was used to send the collected data to a server. An antenna was connected outside the node. Data lines could be connected externally according to actual requirements. The antenna was adjusted to a proper height. The final distribution of acceleration sensors and wireless nodes is shown in Figure 8(b). Data collection was conducted on all the nodes. Acceleration signals on bridge deck and piers were recorded.



(a) Tested regions of wireless sensor network

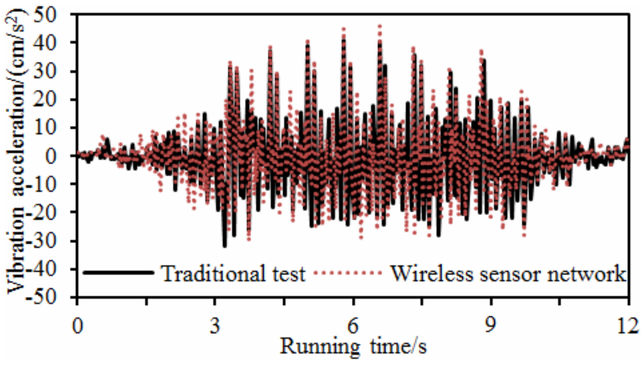


(b) Distribution diagram of network nodes and sensors

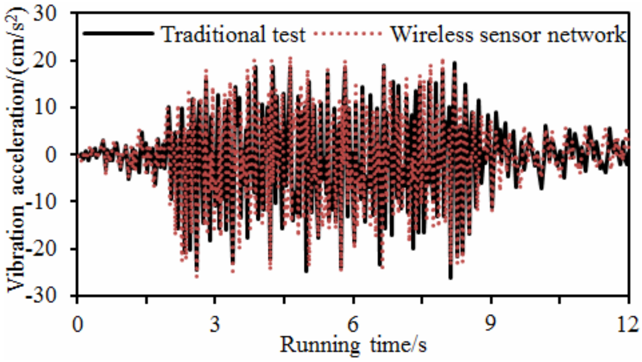
Figure 8. Tested diagram of wireless sensor network

Acceleration signals were processed, so vibration accelerations at each key cross section of the bridge could be obtained. Vibration accelerations at the side mid-span cross section, 1/4 mid-span cross section, mid-span cross section and piers were extracted and compared with tested results of the traditional method, as shown in Figure 9 and Figure 10. It is shown in Figure 9 that the mid-span cross section and the side mid-span cross section of the bridge had the maximum vibration accelerations. Vibration accelerations on the pier cross sections were obviously lower than those at other positions. The reason is that the piers had larger rigidity as a whole and the dynamic responses would be smaller under the same load excitation. It is shown in Figure 9(d), Figure 9(b) and Figure 9(a) that dynamic responses of the bridge cross section developed backwards gradually. The reason is that the train would firstly acted on the side mid-span cross section, then the 1/4 mid-span cross section and finally the mid-span cross section. In addition, the 1/4 mid-span cross section was supported by piers and had large rigidity, so that the vibration accelerations would be smaller. Side mid-span and mid-span cross sections had large spans and small bending rigidity as a whole, so that the vibration acceleration responses would be larger. In addition, horizontal dynamic responses of side mid-span cross sections of the bridge were extracted, as shown in Figure 10. Through comparison between Figure 9 and Figure 10, we can find that horizontal dynamic responses were obviously smaller than vertical responses. Tested results of the WSN and the traditional method approached in varying trends and values. At most peaks, results of the WSN were larger. The reason is that the traditional method adopted a long data line and generated resistance which had reduced voltage signals transmitted to the collection equipment. Therefore, the vibration signals would be weakened. Compared with the traditional method, the WSN had more peaks on several cross sections. As a whole, it is feasible to test bridge dynamic responses using the WSN.

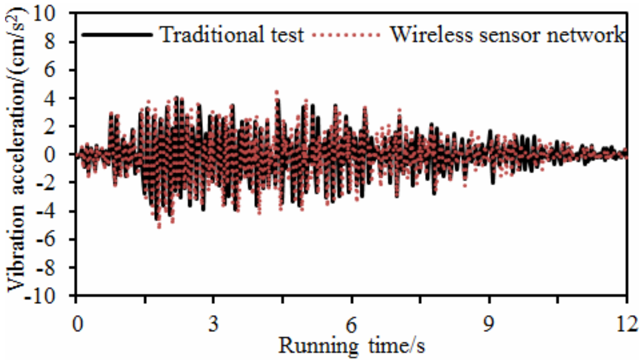
Accelerations tested by the WSN were processed. Therefore, vibration displacements of each key cross section could be obtained, as shown in Figure 11. It is shown in the figure that the mid-span cross section had the largest vibration displacement; the piers had the smallest vibration displacement. In addition, vibration displacements of the mid-span cross section were basically symmetrical. The mentioned analysis results indicate that it is feasible to test vibration accelerations of the bridge using the WSN technology. Therefore, the running speed of the train was changed from 50km/h to 300km/h with the step length of 50km/h. Vibration accelerations of key cross sections of the bridge under each speed were tested, and amplitudes were extracted, as shown in Figure 12. It is shown in the figure that with the increased running speed, the vibration acceleration amplitude of each cross section was increased at first and then decreased. The peak of the side span appeared at the speed of 125km/h. The peak of the mid-span cross section appeared under 200km/h. Peaks of the 1/4 mid-span cross section and the pier appeared under 225km/h. Peaks of each cross section appeared under different speeds as train running under different speeds would cause resonance at different positions, which could generate vibration peaks. Moreover, the biggest peak appeared at the speed of 125km/h because the resonance will be the most serious.



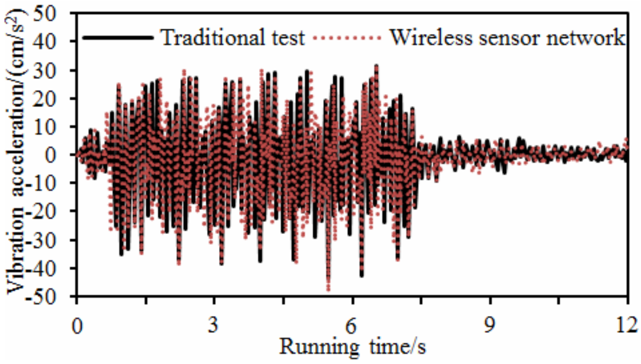
(a) Mid-span cross section



(b) 1/4 span cross section



(c) Pier cross section



(d) Side mid-span cross section

Figure 9. Vertical acceleration on each key cross section of bridges

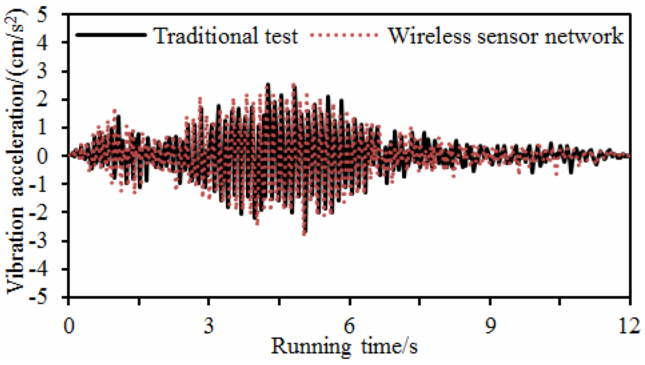


Figure 10. Horizontal acceleration of side mid-span cross section

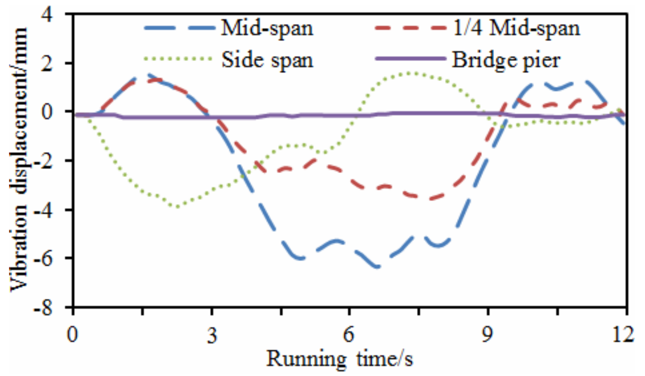


Figure 11. Vibration displacements at each key cross section

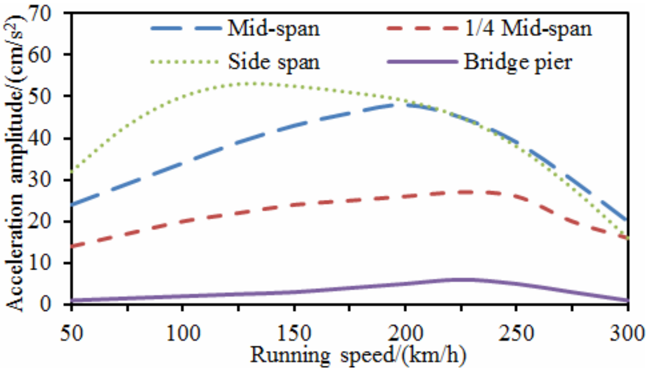


Figure 12. Vibration acceleration amplitudes under different speeds

4 Conclusions

This paper applies WSN technologies to test dynamic responses of a bridge under train effects. Compared with those results of the traditional method, at most peaks, results of the WSN were larger. The reason is that the traditional method adopted a long data line and generated resistance which had reduced voltage signals transmitted to the collection equipment. Therefore, the vibration signals would be weakened. Moreover, the WSN had more peaks on several key cross sections. As a whole, it is feasible to test bridge dynamic responses using the WSN. In addition, we can find that horizontal dynamic responses of bridges were obviously smaller than vertical responses.

With the increased running speed, vibration acceleration amplitudes of each cross section were increased at first and then decreased. Peaks of the side span appeared under 125km/h. Peaks of the mid-span cross section appeared under 200km/h. Peaks of the 1/4 mid-span cross section and the pier appeared under 225km/h. Peaks of each cross section appeared under different speeds as train running under different speeds would cause resonance at different positions, which could generate vibration peaks. In the future, we will try to use the more advanced WSN technology to test the dynamic response of the long-span bridge to reduce the sensor nodes. Also, the tested results will be more accurate.

Acknowledgements

The Project was supported by the Scientific Research Foundation of Guangxi University (Grant No. xtz150324)

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Biography

Nianchun Deng, male, born in 1975, Doctor of Engineering, professor, Main research interests: Construction technology research and equipment development of engineering structure, Health diagnosis and maintenance of engineering structure.