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Structural health monitoring of a high-speed railway bridge: five years review and lessons learned

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Abstract. Based on monitoring data collected from the Nanjing Dashengguan Bridge over the last five years, this paper systematically investigates the effects of temperature field and train loadings on the structural responses of this long-span high-speed railway bridge, and establishes the early warning thresholds for various structural responses. Then, some lessons drawn from the structural health monitoring system of this bridge are summarized. The main context includes: (1) Polynomial regression models are established for monitoring temperature effects on modal frequencies of the main girder and hangers, longitudinal displacements of the bearings, and static strains of the truss members; (2) The correlation between structural vibration accelerations and train speeds is investigated, focusing on the resonance characteristics of the bridge at the specific train speeds; (3) With regard to various static and dynamic responses of the bridge, early warning thresholds are established by using mean control chart analysis and probabilistic analysis; (4) Two lessons are drawn from the experiences in the bridge operation, which involves the lacks of the health monitoring for telescopic devices on the beam-end and bolt fractures in key members of the main truss.

Keywords: structural health monitoring; high-speed railway bridge; long-term monitoring data; bridge response; early warning threshold

1. Introduction

The high-speed railway network in China has been rapidly constructed in the last decade, and the long-span bridges play a vital role in the high-speed railways. However, the performance of the bridges will inevitably deteriorate in the long-term service period, and then worsen the train running stability and even endanger the running safety. To date, bridge-inspection vehicles can only be employed during the "window period" at night, which leads to high cost and inefficiency. Consequently, how to real-time ensure the health of bridge structures has become a crucial research project to the train running performance on high-speed railway bridges.

With the great development of testing technologies in civil engineering, the environmental loads and the structural responses can be accurately obtained. Wiberg and Karoumi (2009) investigated the long-term dynamic responses of an urban railway bridge based on autonomous monitoring. Kosnik and Dowding (2013) analyzed dynamic behavior of a long-span high-speed railway bridge using field test data. Yi *et al*. (2013) studied the wind-induced responses of structure based on the GPS monitoring technology. Ding *et al*. (2015) monitored a high-speed railway bridge structure based on long-term structural health monitoring data. Ye *et al.* (2016) measured the image-based structural dynamic displacement using different multi-object tracking algorithms. Ding *et al.* (2016) analyzed the train-induced hanger vibration of a high-speed railway steel arch bridge by field monitoring results. Ye *et al*. (2018) conducted a stochastic characterization of wind field characteristics nearby an arch bridge based on long-term monitoring data from an instrumented structural health monitoring system.

Base on the analysis of bridge responses, the performance of bridge structure can be assessed. Wang *et al.* (2015) assessed the static performance of a long-span arch bridge by monitoring the correlation between temperature field and its static strains. Guo *et al.* (2015) investigated the cracking of longitudinal diaphragms in long-span cable-stayed bridges used field tested strain data. Wang *et al.* (2016) detected and located the degraded bearings by monitoring the longitudinal expansion performance of the bridge main girder.

Steel-truss arch bridges have been increasingly popular among large-scale bridges chosen by engineers due to their larger stiffness, lower usage of steel and greater capability in span (Zhao *et al*. 2017). What makes the Nanjing Dashengguan Bridge a representative candidate for this research project is not only the significant longitudinal deformation of the steel girder caused by temperature effects but also the obvious vibration responses of rigid hangers activated by excessive train loadings and high train speeds. Hence, an early-warning system is necessary to be established to maintain the safe operation of high-speed

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Fig. 1 Nanjing Dashengguan Bridge

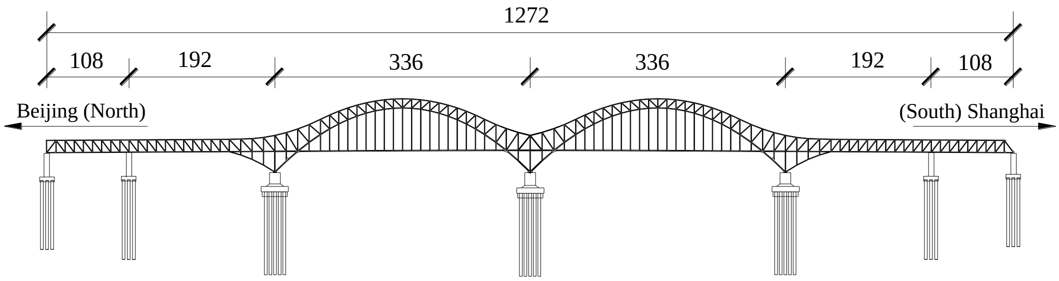


Fig. 2 Elevation view of bridge structure

railway bridges, which follows three steps from "monitoring the effects of environment loadings and train loadings", "early detection of structural deterioration" to "real-time assessment and early-warning of train running safety". This paper has four main sections, where a brief introduction of this bridge structure is introduced, the general design of the structural health monitoring system is presented, and finally, the interpretations of monitoring data as well as lessons learned are discussed.

2. Nanjing Dashengguan Bridge

The Nanjing Dashengguan Bridge is the first six-lanes railway arch bridge in the world as shown in Figs. 1 and 2, composed of two lanes on the downstream side for Beijing-Shanghai (B-S) high-speed railway, two lanes on the upstream side for Shanghai-Wuhan-Chengdu (S-W-C) quasi-high-speed railway and the rest on the outer sides of the bridge deck for Nanjing Metro. It was put into operation in 2011 and at that time the highest train speed of the bridge was designed up to 300 km/h. The whole structure consists of two continuous steel truss girders and a six-span continuous steel truss arches, so that the length of the main bridge reaches 1272 m. Besides, the whole bridge has three rows of rigid hangers, the longest one among which is approximate 60 m. The main truss and transverse contact members mostly apply box sections and H-shaped sections, and the joints of the main truss are connected with bolts. Owing to the fact that the Nanjing Dashengguan Bridge carries extremely heavy train loads, it has to employ specific steel ball bearings. Moreover, special telescopic devices on the beam-end are also installed on the six-span continuous steel truss arch structures. Above all, there are three main factors which play a great role in influencing the bridge structure performance, including the large spans, heavy loads and high train speed. Thus more attention should be paid to these three features when conducting structural health monitoring of high-speed railway bridge.

3. Structural health monitoring system

This section describes the overall design of the structural health monitoring system of the Nanjing Dashengguan Bridge, which contains health monitoring contents, input-output based design, sensor placement and the illustration of train cases.

To determine the monitoring details of this bridge, there are a variety of aspects needed to be taken into account. First, the monitoring contents serve for bridge maintenance management, namely providing scientific bases for maintenance decisions. Second, it needs to consider the particularity of bridge structures, the feasibility of test methods and the reliability of analytical methods. In addition, the effect of environmental changes on bridge structures is so significant that it demands necessary researches and analyses. Table 1 lists the health monitoring contents of the Nanjing Dashengguan Bridge in consistent with diverse monitoring requirements.

Table 1 Monitoring contents for diverse requirements

Monitoring Requirements	Specific contents
Environmental Monitoring	Natural Wind Loads Temperatures Relative Humidity
Dynamic Strain Monitoring	Strains of Arch Members Strains of Girder Members Strains of Cross Beam Strains of Bridge Deck
Dynamic Acceleration Monitoring	Accelerations Amplitudes
Displacement Monitoring	Vertical Displacements in the Mid-Span
Specific Parts Monitoring	Displacements of Bearings
Train Monitoring	Train Speeds Train Numbers Identification

Table 2 Input-output based design

Source Data/ Input Data	Sensors	Eigenvalues/ Output Data
Acceleration of Main Girder	Acceleration Sensor	Acceleration Peak and Root Mean Square Value of Main Girder
Velocity of Main Girder	Velocity sensor	Amplitude and Root Mean Square Value of Main Girder
Acceleration of Main Girder	Acceleration Sensor	Modal Frequency of Main Girder
Velocity of Hangers	Velocity sensor	Amplitude and Root Mean Square Value of Hangers
Acceleration of Hangers	Acceleration Sensor	Modal Frequency of Hangers
Longitudinal Displacement of Bearings	Displacement Sensor	Longitudinal Displacement of Bearings
Strain	Fiber Bragg Grating (FBG) Strain Sensor	Static Strain

The monitoring data collected from the sensors on the Nanjing Dashengguan Bridge is the source data, several types of which can be directly utilized, whereas others must be transmitted to corresponding eigenvalues for next structural analyses. Table 2 presents the input-out relationships between relevant data that mainly discussed in the section "interpretation of monitoring data".

There are totally 124 sensors deployed on 21 cross sections of the Nanjing Dashengguan Bridge, respectively monitoring wind speeds, temperature and humidity, vibration responses of structures, structural strains and deformations, as well as train speeds. The locations of sensors are determined by the mechanical characteristics of this bridge structures. With regard to the data discussed in the section "interpretation of monitoring data", Fig. 3 shows the arrangement of various sensors.

The Nanjing Dashengguan Bridge, which is the shared corridor to cross Yangtze River for both the B-S high-speed railway and the S-W-C quasi-high-speed railway, has complicated train cases when open to high-speed trains. To investigate the resonance characteristics of vehicle-bridge accurately, train loadings are divided into 9 train cases, as shown in Fig. 4. Cases 1, 3, 5, 7 are from Beijing to Shanghai, Cases 2, 4, 6, 8 are from Shanghai to Beijing. Cases 1, 2, 5, 6 are the train load case with 8 train-cars, Cases 3, 4, 7, 8 are the train load case with 8 train-cars. However, due to the testing condition when multiple trains crossing the bridge, the research focus is on the first eight train cases while the ninth case is neglected.

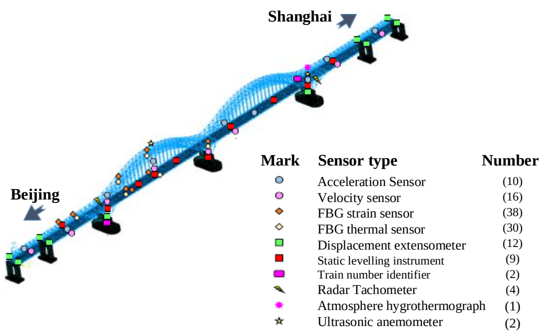


Fig. 3 Arrangements of sensors

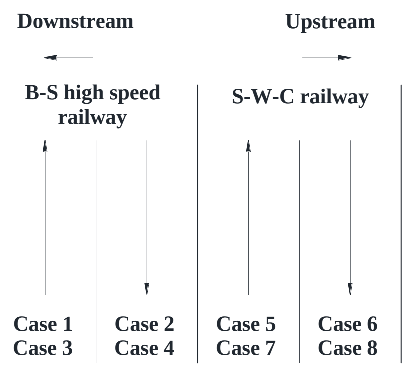


Fig. 4 The first eight train cases

4. Interpretation of monitoring data

4.1 Effect of temperature on monitoring data

4.1.1 Effect of temperature on modal frequencies of the main girder

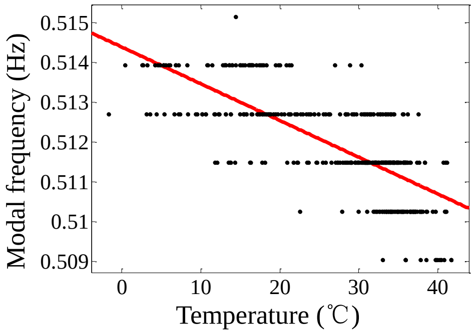
The effect of temperature is one of the most vital factors that affect the mechanical performance of large-scale bridge structures. First, periodogram algorithm is used in the spectrum analysis of vibration accelerations of the main girder. The fast Fourier transformation (Brenner and Rader 1976) is used to obtain the frequency spectrum based on the acceleration data of girder. The peak points of frequency spectrum mean the modal frequencies of bridge girder. One data is obtained for one day. Through processing those monitoring data, which are selected from 0 o'clock to 1 o'clock because of no trains passing, it is pivotal to acquire the daily frequency of the main girder and further investigate the relationship between modal frequencies and structural temperature. Taking modal frequencies from the year of 2014 to 2015 as an example, it indicates that the first-order transverse frequencies and the first-order vertical frequencies both show the cyclical trend, which means they are both impacted by structural temperature. In this part, the least squares method is used to establish the polynomial regression model of modal frequencies and structural temperature. The correlation scatter plots and the fitting lines are presented in Fig. 5. It can be concluded that there is an obvious linear correlation between structural temperature and natural frequencies.

4.1.2 Effect of temperature on modal frequencies of the hanger

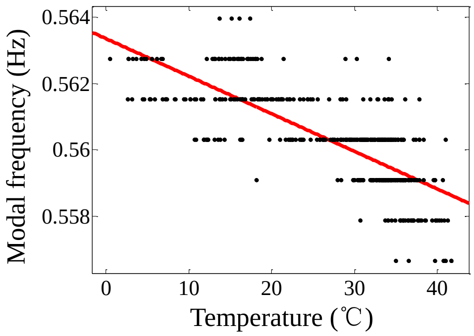
The spectral analysis on vibrating velocities of hangers also applies periodogram algorithm method. Selecting the data from 0 o'clock to 1 o'clock, daily frequency of hangers can be available by processing these data, and then more details about modal frequencies and temperature can be known. As a typical instance, in the year of 2015, the first-order transverse frequencies and the first-order longitudinal frequencies of hangers both present the cyclical trend and are impacted by structural temperature. Fig. 6 demonstrates correlation scatter plots and fitting curves regarding structural temperature and natural frequencies which includes the first transverse frequencies and the first longitudinal frequencies. As shown in the graph, there is an explicit linear correlation between modal frequencies of hangers and structural temperature.

4.1.3 Effect of temperature on the longitudinal displacements of bearings

This part investigates the relation between longitudinal displacements of bearings and structural temperature depending on the monitoring data from March to October in 2013. There are 144 measured displacement values each day because the average displacement value of each bearing is computed with 10-min as time interval. According to the long-term monitoring results, longitudinal displacements of bearings have explicit characteristics of seasonal variation and diurnal variation, implying that there might be a relatively obvious correlation between longitudinal displacements and structural temperature.

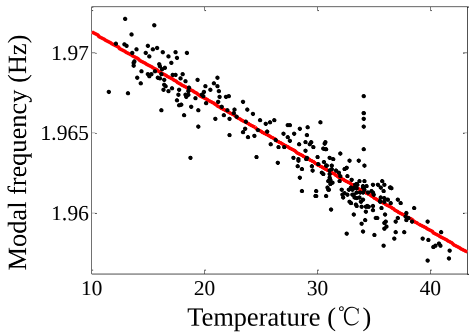


(a) The first-order transverse frequencies

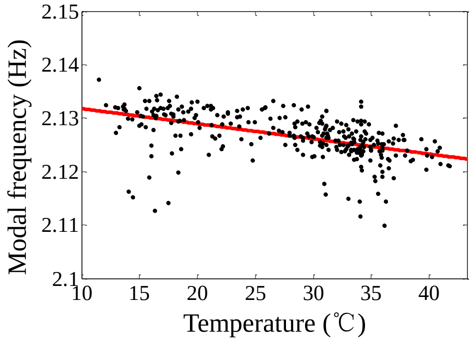


(b) The first-order vertical frequencies

Fig. 5 Correlations between the modal frequencies of main girder and the structural temperature



(a) The first-order transverse frequencies



(b) The first-order longitudinal frequencies

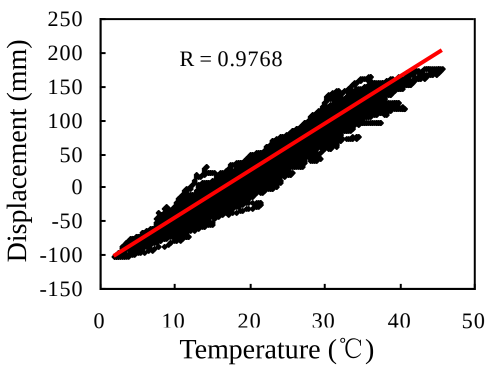
Fig. 6 Correlations between the modal frequencies of hanger and the structural temperature

Linear model approach is applied in order to make a deep investigation of the correlation degree between them. Because all bearings share the similar dynamic variation trend, this part chooses the most typical instance to illustrate the effect of temperature. First, the effect of average structural temperature is discussed in the correlation analysis. Average structural temperature is the mean value of temperatures from 12 sensors installed on this bridge. Fig. 7(a) shows the correlation scatter plot of longitudinal displacements of one bearing and average structural temperature, which indicates the distinctive features that longitudinal displacements increase with average structural temperature. Second, although the correlation is relatively clear and stable, it still shows a certain degree of discreteness. Thus the effect of emperature difference needs to be investigated simultaneously for an accurate model of longitudinal displacements of bearings.

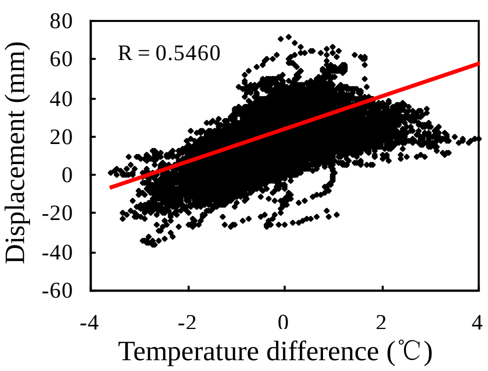
The longitudinal displacement can be normalized to eliminate the effect of average structural temperature via Eq. (1).

$$d_{\mathrm{n}} = d_{\mathrm{m}} - (d_{\mathrm{f}} - d_{\mathrm{r}}) \tag{1}$$

Where d_{n} is the longitudinal displacement after the normalization of temperature; d_{m} is the measured longitudinal displacement, d_{r} is the reference value of each longitudinal displacement (generally the design value or the calculated result of finite element model), and d_{f} is the value of longitudinal displacement from the fitted curve.



(a) Average structural temperature



(b) Temperature difference

Fig. 7 Correlations of longitudinal displacements and temperature field

After eliminating the effect of average structural temperature on longitudinal displacements, as shown in Fig. 7(b), the distribution of data points is relatively decentralized. However, they still have a relatively obvious correlation. It means that the effect of structural temperature difference on longitudinal displacement of the bearing cannot be neglected. To sum up, though the correlation between longitudinal displacements and average temperature/temperature difference is relatively stable, it still presents certain changes, which suggests the long-term monitoring is necessary. Only by the accumulation of long-term data, a more accurate correlation model can be established.

4.1.4 Effect of temperature on the static strains of steel members

According to the former research studies, structural temperature of bridges is correlated to static strains and the correlation can be used to evaluate the static loading capacity of long-span bridges. This part selects the data from March to October in 2013 to investigate the relation between static strains and temperature field, which were collected from two typical sensors. There are 8 strain sensors at the middle section of the northern span of bridge as shown in Fig. 8, and S_i denotes the static strains from the ith strain sensor. After long-time monitoring, the conclusion is that S_1 is mainly impacted by temperature difference while S_2 is influenced by temperature. Additionally, diurnal variation curves of S_1 and S_2 contain a series of "bur" changes caused by train loadings but these effects on static strains are explicitly lower than the effect of temperature field.

Therefore, static strains consist of three compositions, including static strains S_{I} induced by temperature, S_{II} induced by temperature difference and $\mathrm{S}_{\mathrm{III}}$ caused by train loadings. To further study on the correlation between static strains and temperature field, wavelet decomposition method (Mallat 1989) is applied to extract the static strains $\mathrm{S}_{\mathrm{I,II}}$ induced by temperature field. The principle of wavelet packet decomposition for a signal is as follows

Based on two quadruple mirror filters $h_0(k)$ and $h_1(k)$, one discrete signal $x(t)$ can be decomposed scale by scale into different frequency bands

$$x_{0,0}(t) = x(t) \tag{2}$$

$$x_{j+1,2l}(t) = \sum_{i \in Z} h_1(i) x_{j,l}(2^j i - t) \tag{3}$$

$$x_{j+1,2l+1}(t) = \sum_{i \in Z} h_0(i) x_{j+1,l}(2^j i - t) \tag{4}$$

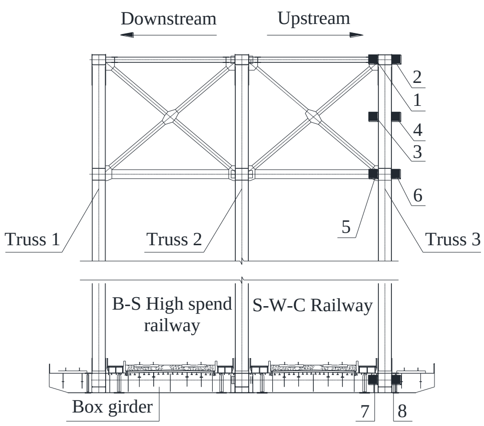
where $x_{j+1,2l}(t)$ and $x_{j+1,2l+1}(t)$ denote the tth values of the signal in the $2l$th and $(2l+1)$th frequency bands of the $(j+1)$th scale, respectively. The signal values in the $(j+1)$th scale can be obtained by the jth scale, so signal values in all scales can be obtained through sequential analogy. The $2l$th and $(2l+1)$th frequency bands are

$[\frac{(2l-1)f_s}{2^{j+1}}, \frac{2lf_s}{2^{j+1}}]$ and $[\frac{2lf_s}{2^{j+1}}, \frac{(2l+1)f_s}{2^{j+1}}]$, respectively, where f_s is the sampling frequency, 2^j is the number of frequency bands in the jth scale.

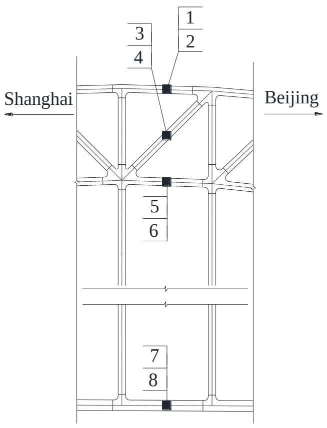
After eliminating the effect of train loadings, Fig. 9 manifests the strong correlation between the maximum and minimum of static strains and temperature field. According to long-term monitoring results, multiple linear regression method is used to establish the polynomial regression model to describe the linear correlation between static strains and temperature field, and then mean control chart analysis is applied to simplify the regression model

4.2 Effect of high-speed train on monitoring data

Due to the serpentine movement of Electric Multiple Units (EMUs), unsmooth rails and loading rates when high-speed trains crossing railway bridges, there is a great potential that the forcing vibration frequency of EMC under a specific train speed is close to the natural frequency or $1/i$ of a certain order frequency (i=1, 2, 3…), which can lead to vehicle-bridge resonance or super-harmonic resonance. The former studies show that train speed is the dominant factor in influencing the loading frequency on the bridge. Thus it is significant to find out the relationship between train speeds and vibration responses of the main girder.

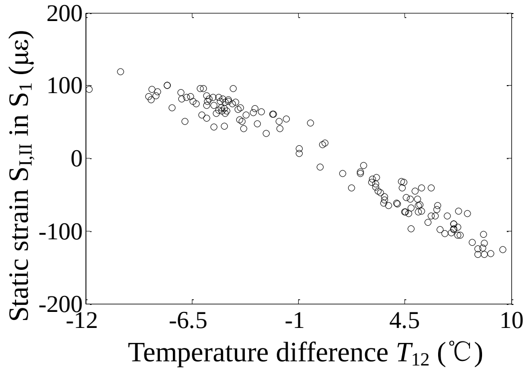


(a) Front view

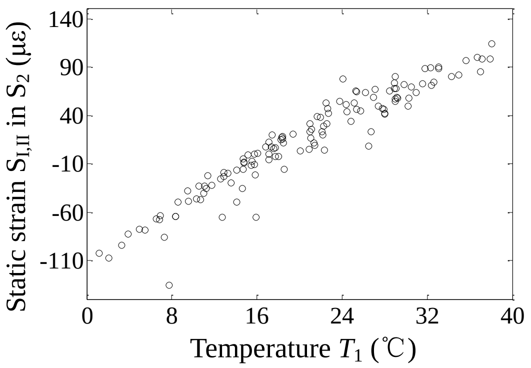


(b) Side view

Fig. 8 Locations of the embedded optical FBG sensors



(a) $S_{I,II}$ in S_1 and temperature difference



(b) $S_{I,II}$ in S_2 and temperature

Fig. 9 Correlations of static strains and temperature field

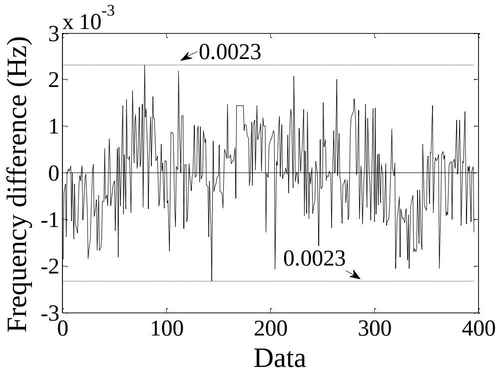
This part analyzes all the data from 2013 to 2015 and discusses the correlation between train speeds and peak accelerations of the main girder. For the purpose of accurately tracking the train speed, average structural temperature and peak accelerations, it is reasonable to only consider the specific data of train speeds and peak accelerations when structural temperature is at the range from 35 to 40℃. It is found that each train case has similar resonance responses, so here one typical train case is picked to illustrate the effect of high-speed train loadings on peak accelerations. Fig. 10 describes correlation scatter plots of train speeds and peak accelerations, which presents a relatively strong relevance between them. There is one or multiple obvious peak train speeds of vibration peak acceleration in the operating train speed range, namely the resonance speed points of vehicle-bridge coupling dynamic response. As shown in Fig. 10, these resonance speed points mainly distribute on the speed ranges from 210 km/h to 220 km/h and 240 km/h to 250 km/h.

4.3 Early-warning thresholds of monitoring data

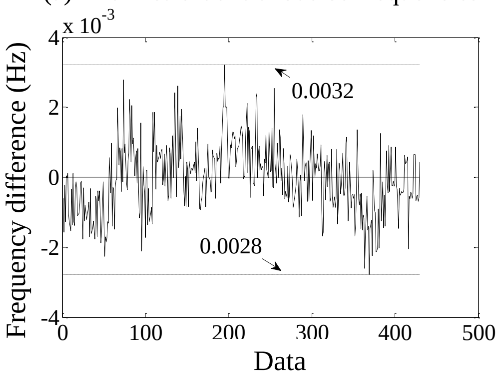
4.3.1 Mean control chart analysis

According to the correlation analysis above, natural frequencies of the main girder and hangers have significant correlations with structural temperatures. They both use mean control chart analysis to establish early-warning thresholds. Based on correlation fitting curves, natural frequencies obtained from monitoring data are normalized, which eliminates the effect of structural temperatures on natural frequencies. Then variation curves of natural frequencies are acquired after the remove of the interference of temperatures, and natural frequency residues impacted by non-temperature factors (structural damage, performance deterioration) are also obtained during long-term service period. The residues and the early-warning thresholds of natural frequencies of main girder are shown in Fig. 11.

The maximum of residues about the first-order transverse frequency is 0.0023 Hz, which is small comparing with the first-order transverse frequency (0.512 Hz). The maximum of residues about the first-order vertical frequency is 0.0032 Hz, which is small comparing with the first-order vertical frequency (0.561 Hz). The natural frequency residues fluctuate is at a small variation range, because the natural frequency (stiffness) of girder is mainly influenced by temperature for an in-serving bridge. Based on the long-term monitoring of natural frequency residues, the limits are set to reflect the normal variation ranges of the dynamic performance of the main girder and hangers, namely early-warning thresholds of natural frequencies of the main girder and hangers. In the long service process, when natural frequency residues exceed the early-warning thresholds, it indicates that the dynamic performance of the main girder and hangers changes distinctly, which further means the stiffness change of the main girder and hangers due to the deterioration or the damage on the main girder components and hangers.

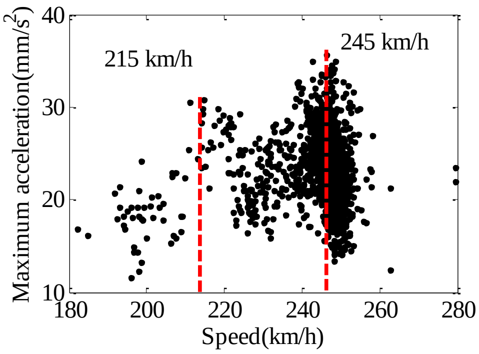


(a) The first-order transverse frequencies

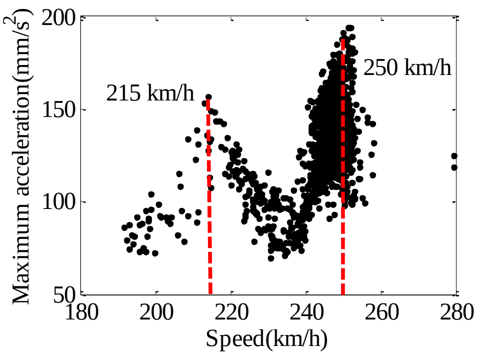


(b) The first-order vertical frequencies

Fig. 11 Residues and early-warning thresholds of modal frequencies of the main girder



(a) Transverse peak acceleration



(b) Vertical peak accelerations

Fig. 10 Correlations between peak accelerations and train speeds

4.3.2 Probabilistic analysis

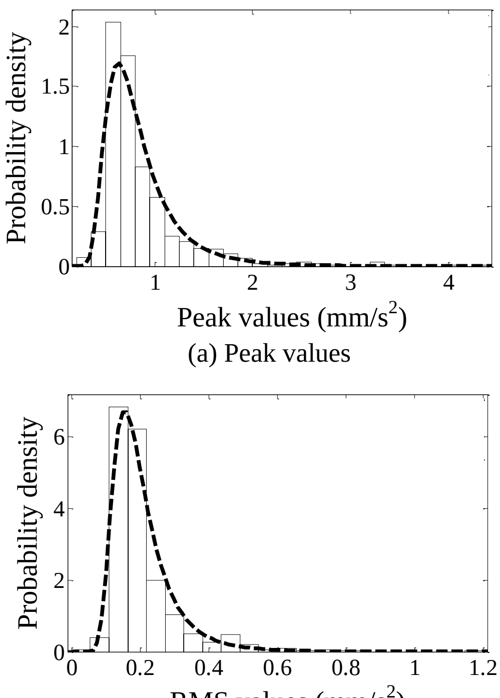
The data which have no correlation with structural temperatures and train speeds presents random changes in the characteristics. Thus probabilistic analysis is used to establish early-warning thresholds based on long-term monitoring results. According to the probability density histogram, it is important to select the appropriate function to describe the statistical properties of data. After comparing the goodness of the fitting of various probability density functions, the Generalized Extreme

Value distribution function is applied to reflect statistical properties of acceleration amplitudes of the main girder and hangers. Taking accelerations of the main girder as an example, this part illustrates the details about how to apply probabilistic analysis to establish early-warning thresholds. First, the least squares method is used to obtain the Generalized Extreme Value distribution function curves in the fitting process. Fig. 12 shows the probability density histograms and their Generalized Extreme Value distribution function curves of transverse accelerations and vertical accelerations of the main girder respectively from January 2014 to December 2015.

Second, the acceleration extreme values and root mean square values are used as the early-warning indexes of vibration performance of the main girder. Each acceleration extreme value and root mean square value represent the maximum and the effective value of accelerations of the main girder under the action of temperatures respectively, which are denoted by d. Acceleration extreme values and root mean square values cannot exceed the corresponding normal value and limit value of the vibration performance of the main girder, which are denoted by [d_{max}]. The normal values and limit values are those extreme values or root mean square values with 5% and 1% transcendence probability respectively. When d is less than [d_{max}], it indicates that the vibration performance of the main girder is in a safe state; while d is equal to or larger than [d_{max}], it means that the vibration performance of the main girder is in an unsafe state and an early-warning signal is essential to notify managers of this bridge. To sum up, based on the probability statistical analysis above, acceleration extreme values and root mean square values with corresponding transcendence probabilities can be directly acquired and finally hierarchical warning thresholds for accelerations of the main girder are obtained.

5. Conclusions

As the presentation in this paper, since the health monitoring system of the Nanjing Dashengguan bridge has been operated for more than 5 years, the overall service performance can be accurately grasped through the analysis of long-term monitoring data, including the vibration performance of main girder and hanger, the service performance of bearings, and the capacity performance of steel truss arch.



(a) Peak values

(b) Root mean square values

Fig. 12 Probability density histograms and their Generalized Extreme Value distribution function curves of transverse accelerations

Based on the structural health monitoring system of long-span railway bridge, the main load effect, such as temperature, train, wind and so on, for each bridge component can be determined; the correlation between the load (input) and the response (output) of bridge structure can be obtained; the normal load effects of component responses can be normalized from monitoring data; the abnormal change of bridge performance in daily operation can be easily detected via the early warning of bridge. This will play a positive role for the operation maintenance and daily management of this bridge.

However, it should be noted that there are some deficiencies in this monitoring system, especially for the insufficient consideration on the monitoring of existing damages after the bridge operation: Lack of monitoring the expansion devices at beam end, the expansion device at the beam has the functions of displacement expansion and bearing capacity, and its mechanical performance and service state are crucial to the running safety and comfort in the area of beam end. The bridge has used abundant high-strength bolts, the fatigue and fracture of the bolts should be online monitored in the bridge operation.

Acknowledgments

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