ISSN : 0974 - 7435 Volume 8 Issue 9

BioTechnology

An Indian Journal

FULL PAPER

BTAIJ, 8(9), 2013 [1311-1317]

Experiment on interface separation detection of concrete-filled steel tubular arch bridge using accelerometer array

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ABSTRACT

The interface separation between the steel tube and the filled-concrete would reduce tremendously the bearing capacity of the concrete-filled steel tubular arch bridge. It is almost impossible to be detected from visual inspection, and there is no efficient method to monitor so far, thus it is a great engineering problem that should be figured out desperately for the sake of safety. In this paper, we proposed a vibration test method of the local mode: distributed accelerometer array is deployed along the tube, and then it is used to record the vibration signal induced by quantitative excitation via telecontrol; at last, the position and size of separation could be determined through the analysis of acquired data. The verified experiment showed that the frequency and amplitude of the signal could represent the state of separation; therefore, we can identify and localize the separation accurately and efficiently.

KEYWORDS

Concrete-filled steel tubular;
Interface separation monitoring;
Vibration test accelerometer;
Quantitative excitation.

INTRODUCTION

Concrete-filled steel tubular (CFST) is a typical example of steel-concrete composite structure, and it is widely applied to arch bridges with the virtue of high bearing capacity and large ductility. According to[1], since the first CFST arch bridge-Wangchang Bridge built in 1990, 229 CFST arch bridges, with spans exceeding 50m, have been built all over China until March 2005, of which the main span of 131 bridges is larger than 100m and 33 larger than 200m. Especially, the clear span of Wushan Changjiang Bridge reaches up to 460m, which is the largest span in the world. It should be aware of that so many long-span CFST arch bridges were built within 15 years on the condition that there is even no special design code for this type of bridge. How is the performance of durability is an imperative problem that every bridge engineer wonders. No one would like to witness the tragedy as the two-way curved arch bridge. It is this problem that constrains the development of CFST arch bridges in recent years.

Unlike suspenders and floor system which are replaceable, the CFST rib is the main bearing carrier, whose bearing capacity and durability dominate the service life of the bridge. Once the interface separation occurs, it will reduce the bearing capacity of the arch bridge[2-5]. pointed out that the interface separation is unavoidable. The occurrence1 of separation rules out the confinement effect and decreases the bearing capacity of the rib consequently. The results of model tests[6-8] showed that the bearing capacity relies on the height, length and circumferential angle of the separation with an inversely proportion. Meanwhile, it is hardly possible to differentiate the position and degree of the damage through appearance inspection. Even though many methods have been proposed, almost none of them could serve a reliable and accuracy insight.

There are hundreds of bridges of this type in China. Accordingly, it is extraordinarily necessary to find a new real-time damage detection method to monitor the CFST rib in order to guarantee the safety of the bridge.

STATE OF ART FOR INTERFACE SEPARATION OF CFST RIB

The research and application of structural health monitoring (SHM) have developed very quickly since the end of the last century. Many SHM systems have been installed in bridges, such as Sutong Cable-stayed Bridge, Runyang Suspension Bridge and Xihoumen Suspension bridge in China. Compared to the cable-stayed bridge and suspension bridge, SHM in CFST arch bridge lags behind: only a small number of bridges have been fixed with SHM system, like Nanning Yonghe Bridge. Besides, there is no special concentration on the monitoring of interface separation[9]. applied modal curvature difference method to diagnose the damage of the rib using finite element method (FEM) numerical simulation. However, the key problem of dynamic damage detection under ambient excitation is how to handle the uncertainty of environment and load conditions, because many researchers have concluded that parameters sensitive to damage are also susceptible to environment and loads. In addition, most cases of damage detection method need the baseline information of overall structure; unfortunately, it is unacquirable in most circumstances[10-12]. As a result, it is not so efficient to identify the local separation using the general vibration test under ambient excitation[13]. employed distributed optical fiber sensor technique to detect the separation in the way of embedding sensors before concrete-pumping. It has been applied in the construction of Wushan Changjiang Bridge successfully, but obviously it cannot be installed in the existing bridges.

In the field of nondestructive test of the interface separation, lots of methods have been put forward, such as ultrasonic detection, impact-echo method and infrared thermography[14-16], whereas all of these methods do not become mature and have difficulties in quantitative detection. Another reason that inhibits the application of these methods is that they are merely suitable for point detection. If we want to obtain the range of separation, a large amount of sensors should be placed along the rib, which is unfeasible from the view of economy and workload.

LOCAL MODE-BASED INTERFACE SEPARATION REAL-TIME MONITOR

Vibration-based damage detection method is the most used in nondestructive test. With advantages of convenience, real-time, and reflecting the general behavior of the structure, dynamic detection has been developing very quickly since 1970s[17,18]. Vibration signals in the frequency domain could represent the general characteristics of the structure quite well; whereas they are not sensitive to the local change, leading to the trouble in diagnosis of the local damage. An ideal method is to obtain the local feature information from the potential damaged area and then to detect the damage based upon certain algorithm[19-21].

The energy of surface wave mainly concentrates on the free surface according to the elastic wave theory. When two media connect closely, the vibration signal only consists of high-frequency components, while it shows low-frequency nature accompanied by large amplitude and slow decay as the separation exists[22,23]. brought forward a method to detect the void beneath a concrete pavement slab based on transient impulse response[24]. developed a similar method to detect the structural silicone sealant damage in hidden frame supported glass curtain wall, on which four accelerometers were fixed to acquire the vibration signal, and then FFT power spectrum was used to analyze the experimental signal.

According to the statistical result, most separations occur in the upper part of CFST circular cross-section. If keep the thickness and radius of tube walls constant, the vibration performance correlates merely with the range of separation. Therefore, the range of interface separation can be monitored and identified via analyzing the change of local frequency and amplitude under quantitative transient excitation.

This paper provides a novel on-line monitoring method for interface separation of CFST arch bridges: the distributed accelerometers array is deployed on the steel tube, and the excitation equipment via remote control implements the quantitative inducement. At last, the acceleration signals recorded are used to detect the interface separation. The layout and framework of the SHM system are illustrated in Figure 1 and Figure 2.

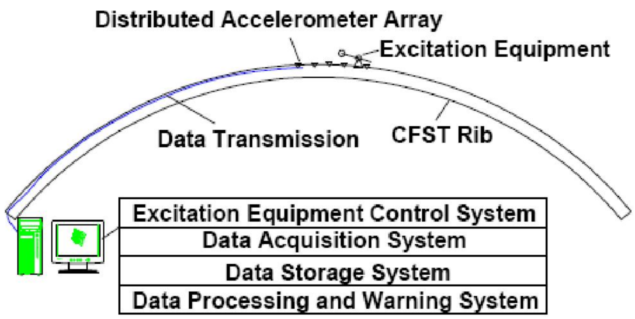


Figure 1 : Layout of SHM system

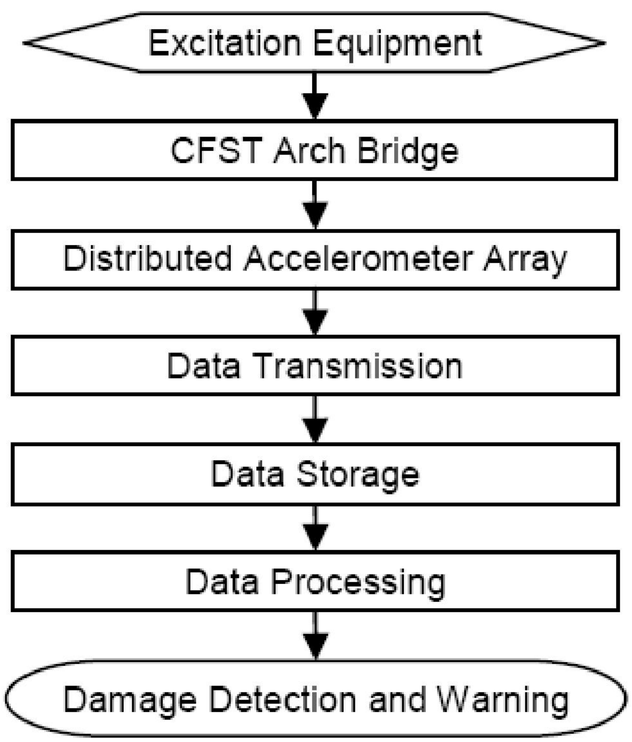


Figure 2 : Framework of SHM system

The pivotal technique of this system is how to judge the existence of separation between the steel tube and concrete. In order to reveal this scientific problem, a validation experiment was carried both on intact plate and separated plate.

THEORY FOUNDATION FOR INTERFACE SEPARATION

Properties of transient impact load

Impact is a kind of transient excitation mainly by means of force-hammer. Various intensities of impact energy can be achieved conveniently by changing the mass and material of hammerhead. Impact load is equivalent to a half sinusioidal wave in time domain, while major energy concentrates within the frequency bandwidth of 0~ f_c (f_c is the frequency corresponding to the intensity of signals decreases 3 db) in frequency domain. The narrower width of the signal in time domain, the larger bandwidth in frequency domain after the Fourier transform. Therefore, the wide bandwidth of excitation is feasible as long as the time of transient excitation is short enough. Thus through the impact load, large numbers of structural mode could be induced so that more damage information can be recorded.

Relationship between frequency and separation

Based on elastic laminiferous vibration theory, the vibration circle frequency of quadrilateral simple supported rectangular thin plate lying on elastic foundation25 is

$$\omega_{mn} = \sqrt{\frac{\pi^4 D}{\rho h}\left|\frac{m^2}{a^2}+\frac{n^2}{b^2}\right| + \frac{k_s}{\rho h}} \qquad (1)$$

where ρ is the density of plate; h is plate thickness; a, b are plate's length and width, respectively; m, n are the frequency orders; k_s is the elastic stiffness of foundation; D is the plate bending stiffness.

When the plate is fixed by other boundary conditions, similar expressions can also be derived as Eq. 1. With the support of concrete, steel plate's vibration is similar to the thin plate on elastic foundation. In the case of interface separation, the steel plate will lose the support from the concrete; correspondingly, the k_s in the formula will disappear, leading the decrease of the natural frequency. Compared with the frequency in the undamaged area, the decline of frequency announces the occurrence of interface separation. The larger the separation range, the smaller the k_s, so vibration frequencies of the steel plate under separation decreases more quickly.

FULL PAPER

A numerical simulation was conducted through finite element method. In this model, the size of the steel plate is 40cm×40cm×6mm. The non-separation domain was constrained by the elastic spring with the rigidity of 1000MPa. The separation area was preset at the center of the steel plate. Several fundamental frequencies for different states of separation were listed in TABLE 1.

TABLE 1 : Fundamental frequencies for different states of steel plate [units: Hz]

States	Non-separation	25×25	15×15	10×10
Fundamental frequency	79185	842.26	2338.4	5256.4

Note: 25×25, et al represent the size of separation domain [units: cm]

It can be seen that the fundamental frequencies will fall down sharply after the occurrence of separation, which tallies well with the theoretical results.

Relationship between amplitude and separation

The general solution 25 of dynamic response of the plate bearing transient excitation $q(x,y,t)=q_0(x,y)f(t)$ is

$$W(x,y,t)=\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}W_{mn}(x,y)T_{mn}(t) \quad (2)$$

where $W_{mn}(x,y)$ is the modal function of the plate, a combination that of beams in the directions of length and width; $T_{mn}(t)$ is the vibration response function, which is related to the impulse and acting position of $q_0(x,y)$.

$$W_{mn}(x,y)=\sum_{m=1}^{p}\sum_{n=1}^{q}A_{mn}X_m(x)Y_n(y) \quad (3)$$

where A_{mn} is an undetermined coefficient; $X_m(x)Y_n(y)$ is the product of two modal function of beams along the corresponding boundary; p,q are the number of modes respectively.

$$T_{mn}(t)=a_{mn}\cos(\omega_{mn}t)+b_{mn}\sin(\omega_{mn}t)+\frac{I\iint_s q_0(x,y)W_{mn}ds}{\omega_{mn}M_{mn}}\sin(\omega_{mn}t) \quad (4)$$

where a_{mn}, b_{mn} are coefficients which are related to the initial condition of the plate; if the initial displacement and velocity are both zero, then $a_{mn}=b_{mn}=0$; $I=\int_0^{t1}f(t)dt$ is the intensity of impulse from $t=0$ to $t=t_1$; $M_{mn}=\iint_s \rho h W_{mn}^2(x,y)ds$ is the generalized mass in m,n order; s is the acting area of loads.

According to Eq. 2-4, the part of low frequency makes more contribution to the amplitude, and the fundamental frequency takes largest share. The amplitude is proportional to the intensity of impulse and the modal function. Therefore, the amplitude should decrease from the center to the boundary within the separated area, while it should be keep almost zero in non-separation area.

EXPERIMENTAL VERTIFICATION

In order to demonstrate the efficiency and feasibility of the proposed identification method, an experiment was implemented, in which the hammer was used to simulate the impulse load, and acceleration signals at various positions were recorded. The location and size of the separation were identified based on the information of frequency, amplitude and damping.

Two test specimens were designed, an intact one and a damaged one, which are shown in Figure 3 and Figure 4, respectively. Concrete platforms with the strength of C30 were directly poured on the solid ground. The size of the concrete platform is 40cm × 40cm × 25cm, and that of the steel plate is 40cm × 40cm × 6mm. The model is shown in Figure 5. In addition, measures were taken on in order to avoid the separation occurring in non-preset area: the expansive agent was added to the concrete to make up the shrinkage, and the experiment was carried on right after the concrete reached the designed strength, so as to circumvent the concrete shrinkage, creep and other factors that may cause the separation. The NIPXI-1045 dynamic experimental system produced by NATIONAL INSTRUMENTS Corp. was adopted, which can acquire and store multi-channel and multi-point accelerometer signals at the same times.

Experimental procedure

Step one: deploy accelerometers at the same measuring points on Specimen 1 and 2, in order to compare the dynamic responses of separation steel plate and non-separation steel plate.

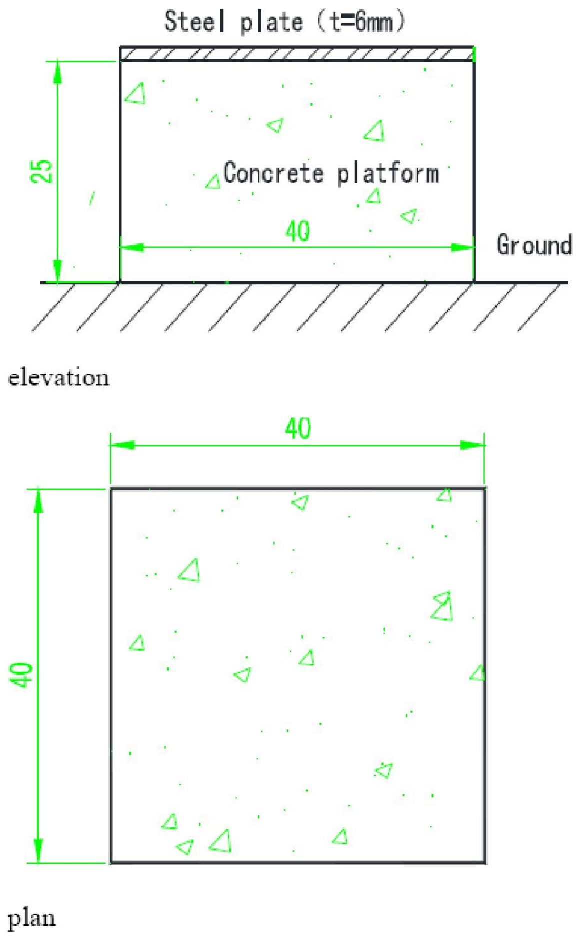


Figure 3 : Layout of specimen 1: intact [unit: cm]

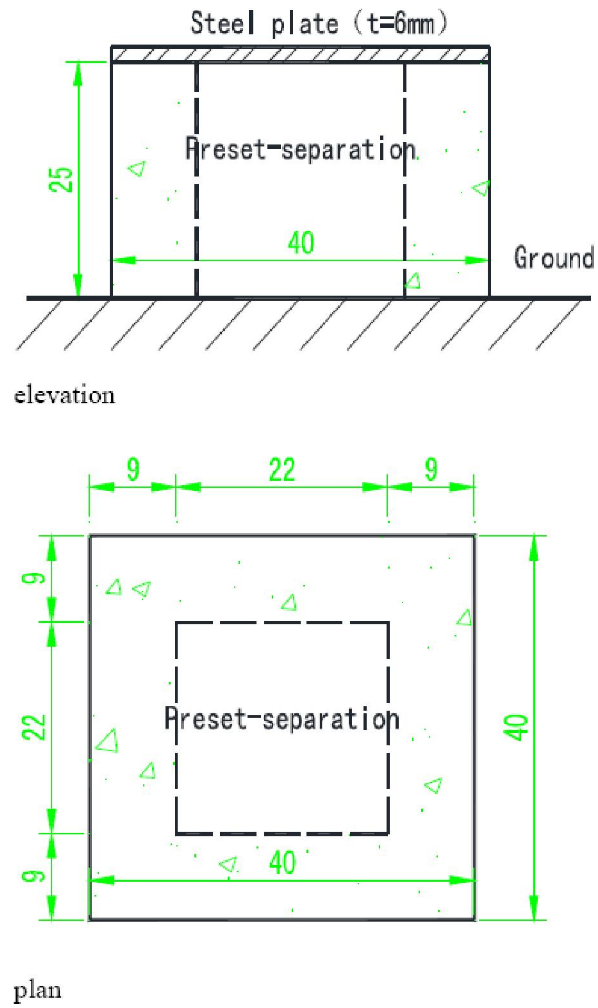


Figure 4 : Layout of specimen 2: damaged [unit: cm]

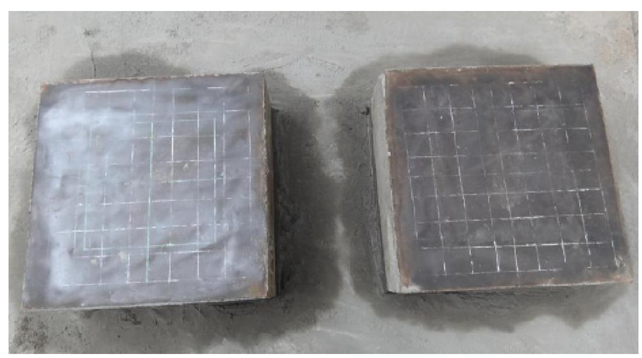


Figure 5 : Experimental model

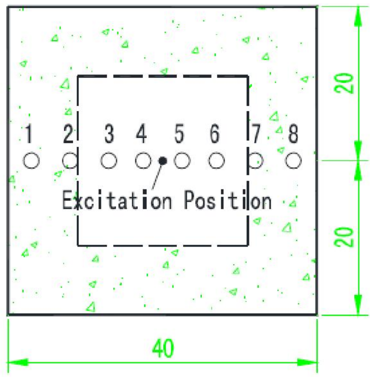
Step two: place eight accelerometers in Specimen 2 with the preset-separation, aimed to identify the separation range by accelerometer signals which were acquired at the same time under the transient excitation. The accelerometer arrays are shown in Fig.6.

Interface separation identification

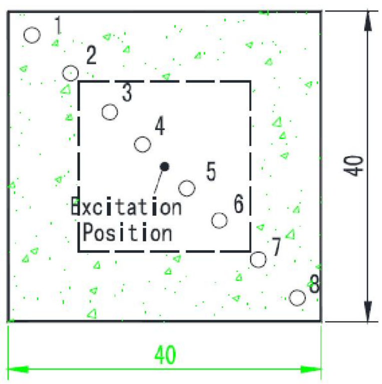
For the test result of Specimen 1, there is no noticeable formant in the acceleration power spectrum, while there are several apparent formants due to the decline of frequencies in Specimen 2, as shown Fig.7.

The results above testified the characteristics that the frequency of steel plate would decrease remarkably after separation. Based on this property, interface separation can be quickly determined, and the separation range might be figured out roughly. In practical application, there are various separation boundaries, and even the same fundamental frequency may correspond to different boundary conditions, so it is unrealistic to identify the separation boundary precisely simply by frequency changes. However, it is quite feasible to build the statistical relationship between the frequency and the most used thickness and radius of tube under typical boundary conditions, and afterward it can be used for the primary identification of separation areas. Large abundance of numerical computations and experiments should be conducted due to the complexity of practical engineering, and this work is under way at present

FULL PAPER

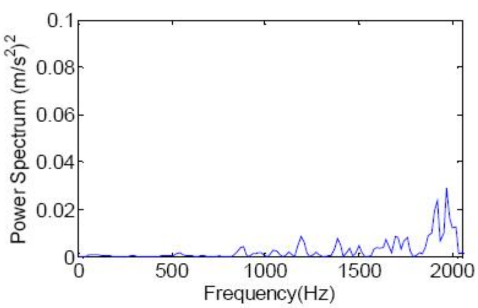


Array 1

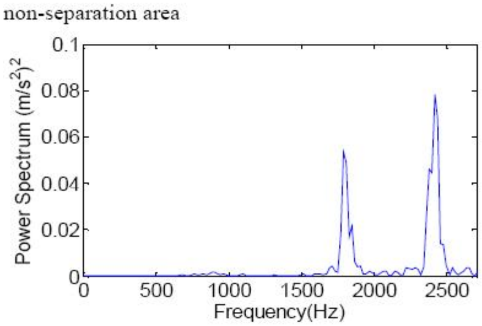


Array 2

Figure 6 : Accelerometer arrays in Step 2 (The number represents the sequence of accelerometers)



non-separation area



separation area

Figure 7 : Acceleration power spectrums

Interface separation range identification

From the recorded signals of Specimen 2, the amplitudes of acceleration in separation area were much higher than those in non-separation domain, and the decay rates were slower simultaneously. In order to obtain the amplitude of the signal, two successive integral were calculated, which was shown in Figure 8. The amplitude would become smaller from the center to the boundary in the separation area, while it keeps in the same level in the non-separation field. When densifying the number of sensors, the accurate boundary could be identified according to the amplitude.

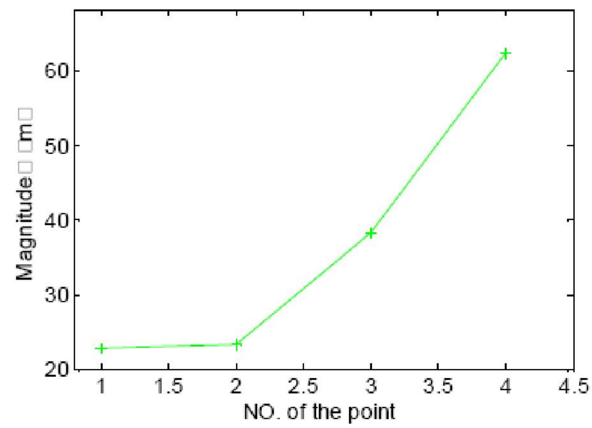


Figure 8 : Amplitudes for different signals

SUMMARIES

Based upon the local mode of steel tube induced by quantitative impact load, the interface separation of CFST arch bridges were identified successfully through frequency shift and amplitude of vibration. The proposed method could be applied to the on-line monitoring of the interface separation via the accelerometer array.

The validating experiment showed:

(1) Once the interface separation appears, the frequency will decline dramatically, and the larger the separation area, the more the frequency reduces, which can be used to judge whether there is a separation.

(2) The intensity of acceleration signal in separation area is obviously higher than that in non-separation area, so is the amplitude. The nearer to the boundary, the smaller the amplitude becomes, while the amplitude is almost the same in non-separation area. Therefore, the separation area can be identified by proper arrangement of the accelerometer array.

In the further study, on one hand, more attention should be paid on the relationship between the separation range and vibrational frequency, amplitude, damping and so on. On the other hand, deep research should be carried on in complete separation, partial separation and some other non-uniform and non-regular separations.

ACKNOWLEDGMENTS

Thanks for the financial supports of National Natural Science Foundation of China (5092100).

REFERENCES

[1] B.Chen; Concrete-filled Steel Tubular Arch Bridge, China Communication Press, Beijing, **(2007)**.
[2] G. Tu; Hunan University PhD dissertation, Changsha, **(2007)**.
[3] L.Tong, G.Xia, M.Wu, X.Shangguan; Highway, **5**, 16 **(2004)**.
[4] D.Rao, H.Hai, Y.Zhang; Railway Engineering, **45**, 14 **(2005)**.
[5] Z.Huang; Hunan University PhD dissertation, Changsha **(2006)**.
[6] S. Yang, F.Wang, P.Qu; J.Chongqing Jiaotong University, **27**, 360 **(2008)**.
[7] Y.Ye, Z.Wen, S.Pan; J.Southwest Jiaotong University, **6**, 381 **(2004)**.
[8] S.Wang; Proceeding of China Road Bridge and Structure Engineering, People Communication, 25 **(1996)**.
[9] K.Xie, H.Lin, S.Liang; J.Guangxi University, **35**, 96 **(2010)**.
[10] H.Kess, D.Adams; Mechanical Systems and Signal Processing, **21**, 2394 **(2007)**.
[11] K.Worden, J.Delieu-Barton; Structural Health Monitoring, **3**, 85 **(2004)**.
[12] W.J.Staszewski; Composites Science and Technology, **62**, 941 **(2002)**.
[13] R.Ding, H.Liu; China Civil Engineering Journal, **38**, 69 **(2005)**.
[14] X.Zhou, Y.Xiao, G.Caol; J.of Railway Science and Engineering, **6**, 50 **(2006)**.
[15] H.Su, W.Lin; Non-Destructive Testing, **6**, 50 **(2006)**
[16] P.Huang, H.Xie, X.Yuan; Laser&Infrared, **34**, 350 **(2004)**.
[17] D.Han, W.Wang; J.of South China University of Technology, **11**, 91 **(2003)**.
[18] A.Li, C.Miu; Bridge Structure Health Monitor, People Communication Press, Beijing, **(2009)**.
[19] J.Ou, H.Li; Structural Health Monitoring, **9**, 219 **(2010)**.
[20] G..Li, J.Li; Engineering Structural Dynamic Detection Theory and Application, Science Press, Beijing, **(2002)**.
[21] W.Yi, G.Wu, L.Xu; J. of Dynamics and Control 4, 363 **(2006)**.
[22] X.Zhang, J.Wang; China Civil Engineering Journal 36, 105 **(2003)**.
[23] Q.Wang, X.Han, Z.Yi; J.of Southwest Jiaotong University, **45**, 718 **(2010)**.
[24] Z.Chen, Y.Luo; J.Gu, Sichuan Building Science, **35**, 104 **(2009)**.
[25] Z.Cao; Plate Shell Vibration Theory, China Railway Press, Beijing, **(1989)**.