Research on health monitoring of Harbin Sifangtai Bridge in China

X.F. Zhao, S.Z. Tian, H. Li, L.Q. Hou & J.P. Ou
Civil Engineering School, Harbin Institute of Technology, Harbin, China

ABSTRACT: Harbin Sifangtai Bridge with 336 meter main span and 696 meter length is located in Harbin city and is the biggest cable stayed bridge with two towers along the songhuajiang river in the Heilongjiang province of China. In order to monitoring the global response and the local strain and temperature of the bridge, and then evaluate the health condition, one health monirong system has been established during two years time, which includes sensors such as accelerometer, fiber Bragg grating strain and temperature sensors, anemoscope. Signals from sensors were led to the central control room located in the main tower. The finit element (FE) model of the bridge has been developed for the purpose of structural health evaluation and installation of the healthmonitoring system. Data obtained during the load test and bridge in-service can show global dynamic response and the local strain response of the key elements were in good condition.

1 INTRODUCTION

Since the service life of typical infrastructure may be of the order of 50 years or more, it is a serious challenge to monitor and evaluate the health condition of the infratructure which was in the process of gradually degrading under various loads, and then make stratagem to maintain the structure. A significant amout of interest in health monitoring and evaluation of infrastructure especially bridges has been generated in the civil engineering community recent years (Han & Xie, 2002; Cornwell *et al*, 1998; Zhou *et al*, 2002). This interest has benefited from the recent maturation of novel sensors application which have brilliant advantage toward the traditional sensors. Fiber Bragg grating (FBG) sensors have many advantages (Maaskant *et al* 1997), such as extremely small physical size and its inherent immunity to electromagnetic especially the durability, over the traditional sensor such as strain gauge. FBG sensors, accelerometer and anemoscope were incorporated to the health monitoring system on Harbin Sifangtai Bridge with 336 meter main span, which is a steel-concrete combination cable stayed bridge. FBG sensors were used to monitoring the strain status of the key elements. Global dynamic response and the force of cables were monitored by the accelerometer. Wind load was monitored by the anemoscope mounted on the top of one tower. The data obtained from the sensors during various stages of the bridge service life can give the clue to evaluate the structure health condition.

2 FE MODELING FOR HEALTH MONITORING

The FE model of the bridge has been developed for the purpose of structural health evaluation and installation of the health monitoring system, as shown in Figure 1. Top structure of the bridge is mainly composed of three parts, such as deck, cable, tower. The deck is mainly composed of three parts also, such as main girder, across girder and pavement board. Main girders with the length of 696 meters are made up of steel I-shape beams connecting with rivets. Main girder is simplified to a elastic contineously supported beam in the FE analysis, and simulated by beam188, one kind of three-dimensional beam cell of ANSYS FE analysis software. Across girder is also stimulated by beam188. Main girder, across girder and pavement board can work together by the mean of shear nail connection between the pavement board and two kind of girders with the help of concrete casting. Pavement board is stimulated by cell shell63. The main tower and cable are stimulated by cell beam 188 and cell link10, respectively. Dynamic and static analysis of the bridge were done. From the results of static analysis shown as Figure 2. we can see maximum compression stress occurs in the loacation of transition pier, and maximum tensile stress occurs in the location of side pier. Most parts

of the main girder are under pression. Due to existence of cables, stress along the middle part of main girder is comparatively uniform.

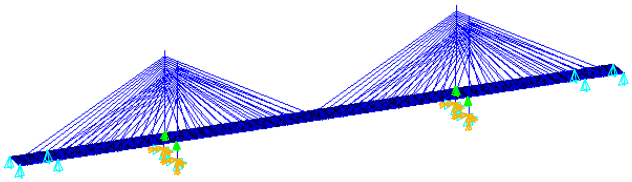

Figure 1. FE model of Sifangtai bridge

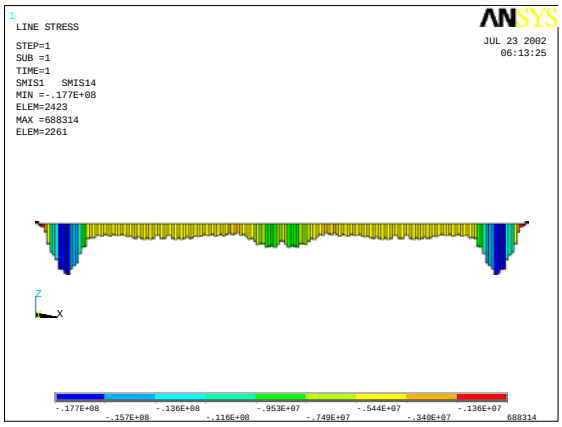

Figure 2. axile stess of main girder

Model for the purpose of health monitoring and evaluation should be built on the basis of transition theory for linking elements between local scale at material points and full-scale at the strucral level[5]. There are difference between the calculation results and monitored results, model updating technique is necessary for an accurate model.

3 LOCAL STRAIN MONITORING

3.1 *Installation of FBG sensor*

On the basis of Sifangtai bridge FE analysis, stress response of structure was concluded. Scheme of FBG sensor installation was made, according to stucture stress distribution and hot point stress principle. FBG strain and temperature sensors were mounted to monitor local strain and temperature of key elements.

Construction of Sifangtai Bridge has characteristics, such as large work space, long time span, complexity of constructing, etc, which increased the difficultes of both installation and protection of FBG sensors and signal wire. There was more than 18-months-period from the beginning of sensor installation to being open to traffic. During the long construction period, only one broken point along one hundred-meter signal wire could arouse the failure of corresponding FBG sensors. In order to ensure the effective installation of sensors, following measures are considered: using steel channel along the bridge to protect the long signal wire from the installation section to central controlling room. The FBG sensors were installed by means of glue. According to the experiment, suitable epoxy glue was choosen to mout sensors on steel element.

According to the design principle mentioned above, construction schedule, and symmetry character of bridge, three monitoring sections located in southern part of bridge were proposed, as Figure 3 shown. ZM1 monitoring section is located in the joint part of southern tower and bridge deck. ZM2 section is located in the mid span of bridge. ZM3 section is located in the joint part of southern side cable and bridge deck. Sixty FBG sensors were installed totally.

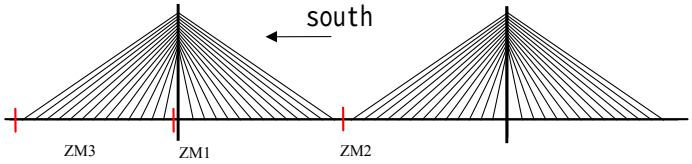

Figure 3. monitoring section of FBG sensors

Every monitoring section is made up of three sub- monitoring section. two sub-sections are located in mid point of upriver and downriver longitudinal girders respectively. the other is located in the mid point of across girder between two longitudinal girders. Intallation of FBG sensors on longitudinal and across sub-sections is shown as Figure 4 and Figure 5.

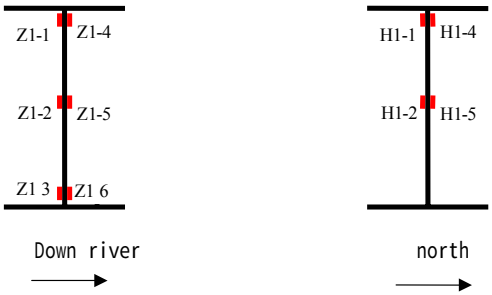

Figure 4. FBG monitoring point on sub-section

Figure 5. FBG installation on across girder

3.2 *Data acquisition device*

Si425 FBG interrogator with four channel, was used to interrogate FBG sensors.In order to overcome the difficulties, such as costly interrogator, less amount of channel, etc, 24×1 optic switches were used to collect the signals to one interrogator with four channels. Then one controlling program which can control the switching interval, switching speed and the sequence of switch channel was made. The wavelength range of interrogator is from 1520nm~1570nm. Resolution for every channel is 0.2pm. The max sampling rate of interrogator is 250Hz. The switch time of optic switch is less than 10ms.

3.3 *Result analysis of completion load test*

3.3.1 *Static result*

Strains and temperature were monitored during the static and dynamic load experiment. The table 1 shows the result of 2th static load case of static load experiment from three monitoring sections. 24 trucks were loaded at the mid span position, symmetrically. 12 trucks were loaded at upriver side. The others were loaded at downriver side. Totally 7200KN is loaded to monitor the response of bridge in static way. From the results shown as table 1, we can draw a conclusion that stress reponses from uperriver and downriver side are basically identical. Maximum tensile stress (81.48 MPa) occurred in the location of upriver longitudinal girder's lower point in ZM2 section. results shows that the stress response are in reasonable range.

Table 1 Static results of 2th load case(MPa)

ZM2 section			
position	upriver	downriver	Across
Uper	2.52	2.52	0.42
Axes	33.18	32.97	—
Lower	81.48	70.14	10.71
ZM1 section			
position	upriver	downriver	Across
Uper	-3.15	-3.36	—
Axes	-2.52	-2.31	—
Lower	-2.52	-2.1	-1.47
ZM3 section			
position	upriver	downriver	Across
Uper	-3.57	—	
Axes	10.29	10.5	
Lower	20.16	21.63	

Since the loading section of 2th load case is located in ZM2, the FBG sensors of this section is more sensitive to the load than others. figure 6 shows the strain results of upriver longitudinal girder monitored by ZM2-Z1-1~3 FBG sensors in two load cycle of 2th load case. We can draw a conclusion that strain responses monitored by FBG sensors under the same load level are identical.

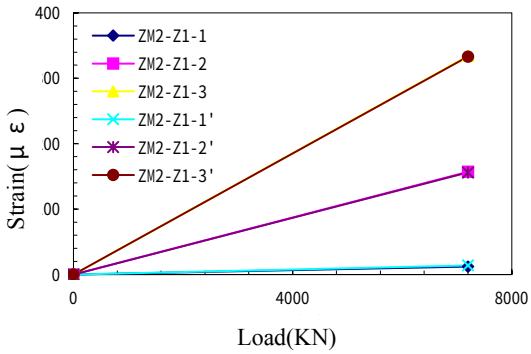

Figure 6. ZM2-Z1-1~3 strain result in 2th load case

To ensure that local strain of key elements can be monitored completely in case of sensor failure, FBG sensors were installed with redundancy. At the same height position of an I-shaped across section, two FBG sensors were installed on two sides respectively. The strain measured by this two sensors should be the same. Figure 7 shows the results of three couple of FBG sensors from ZM2's three sub-section , every couple of sensors are in the same across section height. We can draw a conclusion that every couple of FBG sensor have same result, basically.

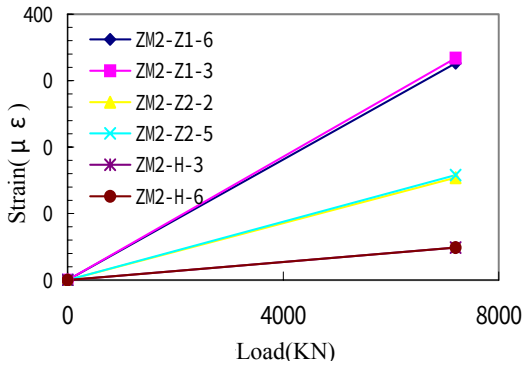

Figure 7. comparision of sensors in the same section height

2th load case is symmetric load, and bridge structure is also symmetric. The elastic strain response shoud be symmetric too. Figure 8 shows the results from upriver girder and downriver girder of ZM2. We can draw a conclusion that the results from symmetric sensors are identical basically.

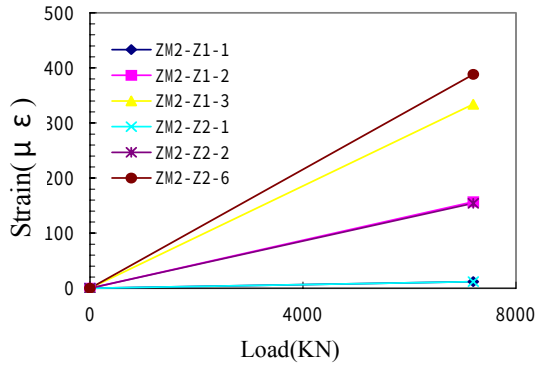

Figure 8. comparision of sensors in symmetric

As figure 6~8 shown, we can draw a conclusion as followed: FBG sensor have good repeatability in two load cycle; results of two FBG sensors with same section height in one monitoring section are in good agreement; results of two FBG sensors in symmetric position are in good agreement, under symmetric load.

Figure 9 shows the stress results monitored by three FBG sensors along section height in one longitudinal girder section in 2th load case. There is a linear relationship between the stress and sectionhight. This shows that longitudinal girder's performance obeyed plan section assumption.

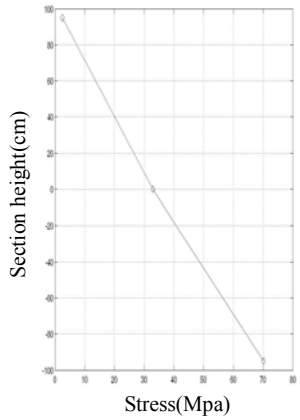

Figure 9. relationship between stress and sectionheight

3.3.2 *Dynamic result*

Respectively, two trucks moved through the bridge at the speed of 10, 20, 30, 40, 50 and 60 km/h, from the same direction and at the same time. Figure 10 shows the strain result monitored by FBG sensors during danymic load test. The curve with bigger response is from upriver girder's uper side of ZM2 section. The curve with little response is from upriver girder's uper side of ZM3 section. The speed of trucks is 60Km/h. Maximum tensile strain(106με) occurred in ZM2 section. Maximum compression strain(-18με) occurred in ZM3. Strain response of ZM2 is more bigger than ZM3. The strain response are in the reasonable design range.

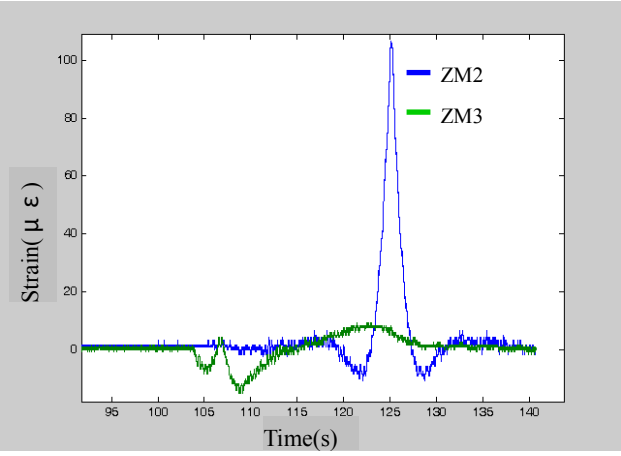

Figure 10. dynamic strain response in dynamic test

3.4 *In-service monitoring resultc*

Harbin Sifangtai bridge was opened to traffic, oct.2004. bridge is one part of Harbin circle highway. A majority of vehicle load is composed by heavy trucks. Figure 11 shows the dynamic strain response of upriver girder's lower point of ZM2 section , which arosed by various vehicle passed through the bridge in 25 minutes. There are many strain peaks which arosed by various vehicle with different weight. Figure 12 shows the local response near the maximum strain peak of Figure 11.

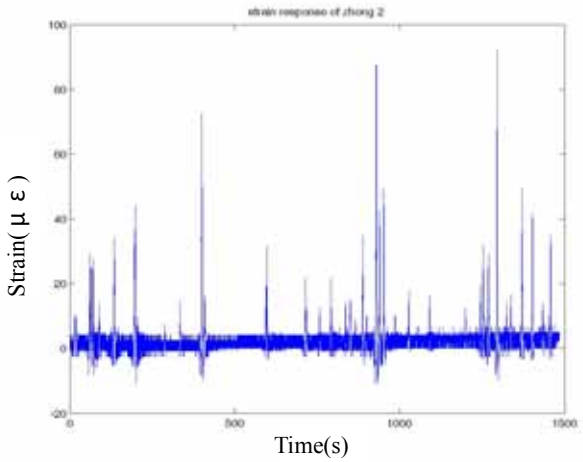

Figure 11. dynamic strain response of ZM2

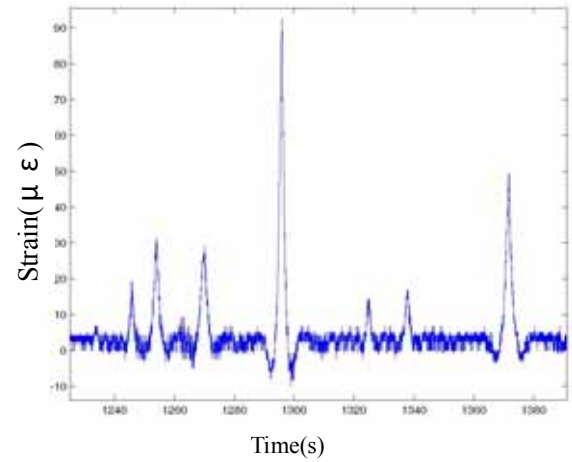

Figure 12. local dynamic strain response of ZM2

Vehicle amount, vehicle load can be estimated, by the strain peak amount, strain peak width, strain peak height of dynamic strain time history curves. There are about 50 peaks in the curve. The biggest strain peak is 93 μ ε , the lowest peak is about 5 μ ε . The results show that the bridge is under good condition.

4 WIND LOAD MONITORING

Wind load is one kind of important dynamic load of bridge structure. Main component of bridge, such as cable, tower and main girder, will vibrate under

wind load. This will result in structure fatigue damage accumulation, and degradation of bridge resistance. It is necessary to monitoring the wind load. One Ultrasonic anemoscope was mounted on the top of southern downriver tower to monitor the windspeed, wind direction and wind attack angle.

4.1 *Device and software*

81000V three-dimensional ultrasonic anemoscope was mounted. Performance of this device as mentioned below: wind speed range:0-40m/s, wind speed resolution:0.01m/s, wind direction range:0.0-359.9 degree. One data acquisition program was developed using Labview as shown in Figure 13.

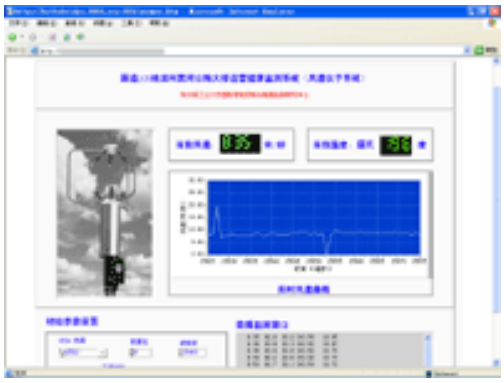

Figure 13. user interface of acquisiton program

4.2 *Monitoring result*

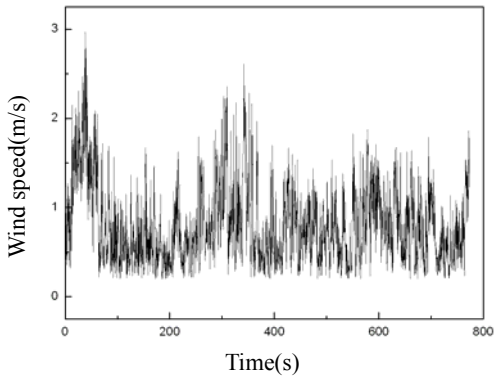

Figure 14. wind speed result

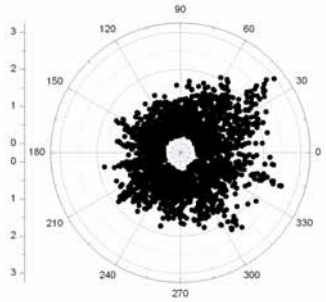

Figure 15. wind direction result

Figures 14 and 15 show the wind speed and wind direction results monitored. From the result, the wind load can be estimated.

5 CABLE FORCE MONITORING

Cable force status is an important sign to judge whether bridge structure is under good condition. Method of cable force measurement is to monitor the vibration frequency of cable, and then conclude the cable force.

5.1 *Installation of accelerometer*

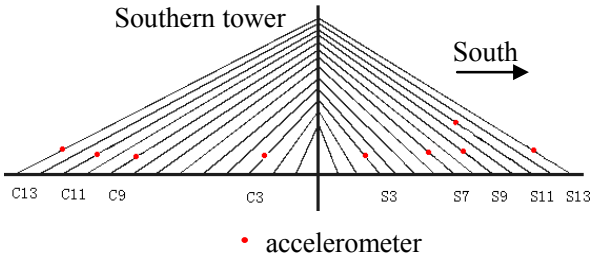

Figure 16. cable force monitoring scheme

On the basis of FE analysis of cables under various load case, such as dead load, vehicle live load, temperature load and wind load etc, 9 cables in the downriver side were seclected to be monitored in the long term, as Figure 16 Shown.

5.2 *Result analysis*

In order to got the information of cable force more comprehensively. After the bridge's opening to traffic, not only the 9 cables but also others cable in the downriver side were measured. Totally, 52 cable's force were measured. Figure 17 and 18 show the typical acceleration time history curve and power spectrum of acceleration time history curve, respectively. Power spectrum reflects vibration character of cable distinctly, that peaks distributes with equal interval.

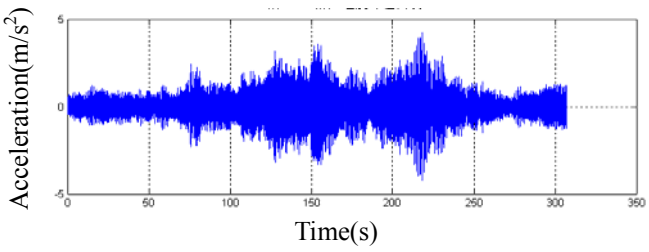

Figure 17. time history curve of acceleration

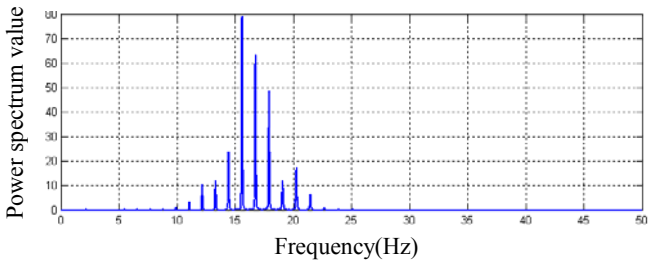

Figure 18. self power spectrum of time history curve

Table 2 shows the results of 26 cables (S01-S13 and C01-C13) at the southern part of bridge.

Table 2. Cable force results (KN)

No.	Cable force measured	No.	Cable force measured	Design cable force
S01	4512	**C01**	3858.9	3939.6
S02	4650.1	**C02**	3834.4	3939.6
S03	4042.3	**C03**	3681.4	3939.6
S04	4663	**C04**	4314.2	4519.6
S05	4609.2	**C05**	4344.7	4519.6
S06	5747.6	**C06**	5563.9	5824.4
S07	4458.1	**C07**	5387.7	5824.4
S08	5507.9	**C08**	5991.3	5824.4
S09	5878.6	**C09**	5956.0	5824.4
S10	5891.7	**C10**	6110.1	6404.4
S11	7576.4	**C11**	7367.3	7274.8
S12	7860.9	**C12**	7433.8	8144.8
S13	8753	**C13**	8644.9	8869.6

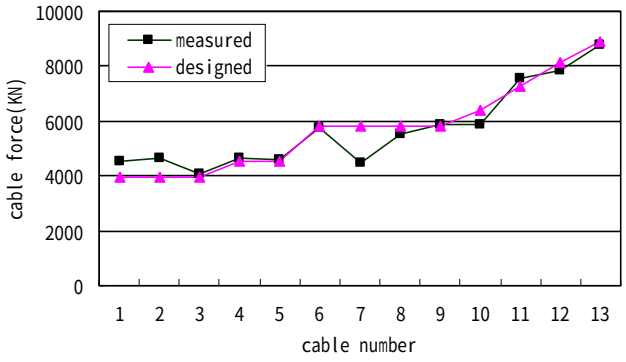

Figure 19. result comparison of cable S01-S13

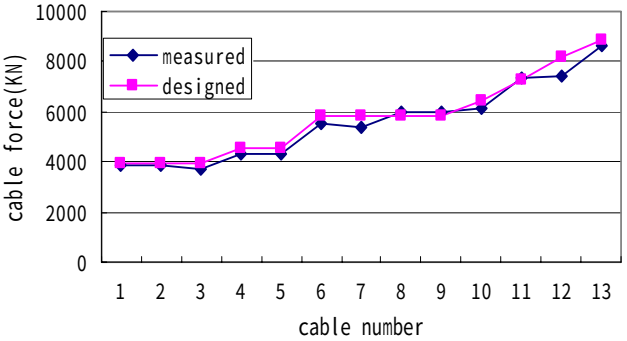

Figure 20. result comparison of cable C01-C13

Cable force of S01,S02,S07 and S10 are not in good agreement with designed cable force, as Figure 19 shown. Cable force of C07, C12 are not in good agreement with designed cable force, as figure 20 shown. The others are in good agreement with designed cable force.

6 VIBRATION MONITORING

Vibration characteristics (vibration frequency, vibration shape and damper ratio) of bridge is determined by structure characteristics, such as material feature, structure stiffness and mass distribution. Vibration characteristic is the key to structure dynamic calculation, analysis of aseismatic and wind load stableness. Vibration characteristic can be calculated, except the damper ratio. However, there is often difference between calculation model and real structure, it is very needed to measure the real vibration characteristic of structure using accelerometer, wich is important to the evaluation of structure damage in the future.

6.1 *Installation of accelerometer*

For the vibration shape measurement need big amout of monitoring sections and sensors, installation scheme was made to measure vibration frequency and damper only, considering economical efficiency. Two accelerometers were installed at two locations of bridge deck near S12 and S13 cable, respectively.

6.2 *Result analysis*

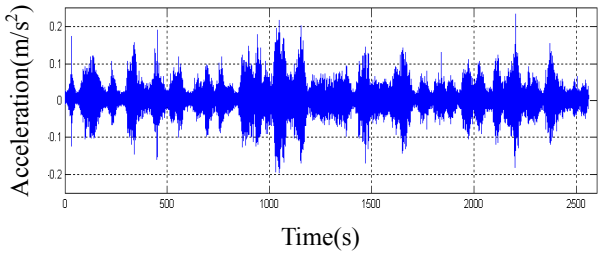

Figure 21. acceleration time history of sensor near S13

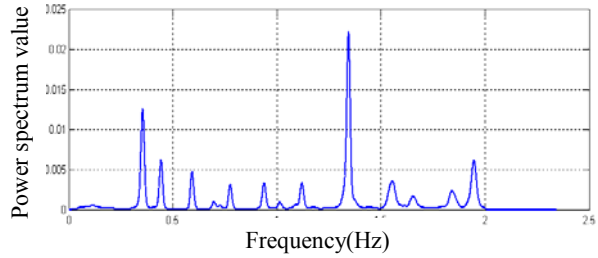

Figure 22. self power spectrum of sensor near S13

Figures 21 and 22 show the acceleration time history and self power spectrum of sensor near S13. Peak pick method (pp method) is used to identify

vibration frequency. Damper ratio and frequency indentified are shown as table 4.

Table 4 damper ritio indentification result

	1th order	2th order	3th order
longitud.	0.00195		
vertical	0.0361	0.0264	0.0176
torsion	0.0189	0.0198	0.0122
transversal	0.00938		
Frequency identification result(Hz)			
	1th order	2th order	3th order
longitud.	0.035		
vertical	0.356	0.443	0.820
torsion	0.593	0.780	1.015
transversal	0.697		

7 CONCLUSIONS

Several kinds of sensor include FBG sensors, accelerometer and anemoscope was integrated to health monitoring system, on the basis of FE analysis. Local strain of key elements, cable force and vibration characteristics of key element were monitored during the completion test and in-service period. The results show that Sifangtai bridge is in good condition.

ACKNOWLEDGEMNETS

This paper was supported by the project In-service Monitoring System of Harbin Songhuajiang Cable Stayed Bridge in collaboration with Communication Bureau of Heilongjiang Province and NSFC under grant No.50420120133. The authors wish to thank Highway Investigation Design Institute of Heilongjiang Province. It is grateful that Harbin Engineering Headquarter of City Circle Highway Construction supports this research work.

REFERENCE

1. Han, D. & Xie, J. 2002. State-of-arts of health monitoring techniques for long span bridge; Bridge Construction, pp.69-73, June.
2. Cornwell, P. J. , Kam, M. K., Carlson, B. *et al*. 1998. Comparative Study of Vibration2based Damage id Algorithms [A] . In : Proc. of 16th International Modal Analysis Conference. Santa Barbara , USA: 1710 - 1716.
3. Zhou, T., L. Guo & Chen, H. 2002. Fatigue evaluation of Tsing-ma bridge subjected to traffic load, Eearthquake Engineering and Engineering Vibration, pp.24-29, Oct
4. Maaskant, R., Alavie, T. & Measures, R. M. 1997. Fiber-optic Bragg grating sensors for bridge monitoring; Cement and Concrete Composites, pp.21-33, July
5. Li, Z., Qun, A. & Chen, H. 2003. Finite element modeling for health monitoring and condition assessment of long-span bridges, Journal of Southern East University, pp.562-572, Sept.