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Operational modal identification of suspension bridge based on structural health monitoring system

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Abstract: An output-only modal identification method by a combination use of the peak-picking method and the cross spectrum methods are presented. Meanwhile, a novel mode shape optimum method of the deck is proposed. The methods are applied to the operational modal identification system of the Runyang Suspension Bridge, which can be used to obtain the modal parameters of the bridge from out-only data sets collected by its structural health monitoring system (SHMS). As an example, the vibration response data of the deck, cable and tower recorded during typhoon Matsa excitation are used to illustrate the program application. Some of the modal frequencies observed from deck vibration responses are also found in the vibration responses of the cable and the tower. The results show that some modal shapes of the deck are strongly coupled with the cable and the tower. By comparing the identification results from the operational modal system with those from field measurements, a good agreement between them is achieved, but some modal frequencies identified from the operational modal identification system (OMIS), such as L1 and L2, obviously decrease compared with those from the field measurements.

Key words: suspension bridge; operational modal identification; structural health monitoring system; ambient vibration test

Cable-supported bridges, due to their high stresses, have some complex dynamic properties, such as wind sensitivity, nonlinearity and time-variation. So it is difficult to analyze dynamic behaviors by the finite element method. The operational modal identification system can obtain the vibration responses and operation modal parameters, which are not only used to verify and modify the finite element model, but also have applications in nonlinear and time-varying dynamic property analysis[1-3].

Moreover, large civil infrastructures such as long-span bridges must be periodically inspected to ensure structural integrity. In the last few decades, enormous resources have been dedicated to the development of a reliable structural health monitoring system (SHMS). Among the variety of damage detection methods, modal-based techniques have been the most widely investigated due to their global nature and simplicity. Modal-based methods exploit the observable variation in modal parameters before and after the presence of defects in the structure. An overview and comparison of output-only modal parameter estimation methods can be found in Refs. [4 – 6]. So far, more studies for analyzing ambient vibration tests of bridges have been conducted[7-8]. However, there are few reports about how to obtain modal parameters from the SHMS.

In this paper, the Runyang Suspension Bridge is taken as the engineering background to study the operational modal identification system. An output-only modal identification method is improved and used to obtain the operational modal parameters of the suspension bridge. Meanwhile, a novel mode shape optimum method is proposed.

1 Operational Modal Identification Method

1.1 Main principle

The operational modal identification method, also designed as the output-only modal identification method, identifies structural modal parameters (natural frequencies, mode shapes and modal damping ratios) using out-only response. Usually the output-only modal identification method is based on the assumption that the input does not contain any information; in other words, the input is white noise. The theoretical assumption of white noise turns out to be not too strict in practical applications. As long as the input spectrum is quite flat, output-only methods will work fine.

In this paper, an output-only modal identification method by a combination use of the peak-picking method and the cross spectrum method is applied to the system. A basic step of the method is the evaluation of spectral estimates of the ambient structural responses from the measured time series. The main steps can be illustrated as follows:

1) Calculate the auto-spectral densities (ASD) or power-spectral density (PSD) of all measured points and obtain an average normalized power spectral density function (ANPSD). The natural frequencies can be identified in terms of spectral peak response (peak picking).

2) Calculate mode shape and damping of all orders. For the identification of the mode shapes, it can be shown that the ratio between a cross spectra $S_{i,j}$ and an auto spectrum $S_{j,j}$, evaluated for a resonant frequency, is a complex value with an amplitude that provides an estimate of a ratio between the modal coordinates at points i and j of the mode shape associated with the considered resonant frequency. The phase of the complex number indicates whether the points are moving in the same sense (zero phase values) or in the opposite senses (π rad phase values). In the context of the PP method, the identification of modal damping coefficients is usually performed using the half-power bandwidth method, but the resulting estimates are not reliable.

3) Obtain the optimum mode shape. Compared with other methods, the traditional peak-picking method has some advantages such as simplicity, practicality, and so on. In order to obtain accurate mode shapes, more measure sensors need to be used, which will lead to high costs. To identify more mode shapes using fewer measured points, a novel mode shape optimum method is proposed, which builds a mathematical model of a bridge deck vertical vibration shape[9].

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1.2 Mode shape optimum

Given that the ratio of length to width of the deck is very high, the vertical vibration of the deck can be seen as a bending vibration of the beam. The ordinary differential equation can be described as

$$\frac{\mathrm{d}^4 y(x)}{\mathrm{d}x^4} - \lambda^4 y(x) = 0 \tag{1}$$

$$\lambda^4 = \frac{\omega_k^2 \rho(x) A(x)}{EI(x)} \tag{2}$$

where $y(x)$ is the vertical displacement of the beam; $EI(x)$ is the stiffness function; $\rho(x)$ is the mass function per unit length, and $A(x)$ is the area function.

The general solution of Eq. (1) is

$$y(x) = A_1 S(\lambda x) + A_2 T(\lambda x) + A_3 U(\lambda x) + A_4 V(\lambda x) \tag{3}$$

where

$$\left.\begin{aligned} S(\lambda x) &= (\cosh(\lambda x) + \cos(\lambda x))/2 \\ T(\lambda x) &= (\sinh(\lambda x) + \sin(\lambda x))/2 \\ U(\lambda x) &= (\cosh(\lambda x) - \cos(\lambda x))/2 \\ V(\lambda x) &= (\sinh(\lambda x) - \sin(\lambda x))/2 \end{aligned}\right\} \tag{4}$$

This solution contains four unknown constants A_1, A_2, A_3, and A_4. By substituting four boundary conditions in Eq. (3), the four constants can be determined.

Given that $Y_k(n)$ is the k-th measured mode shape, then Eq. (3) can be expressed as

$$\boldsymbol{Y}_k = \boldsymbol{CA} \tag{5}$$

where $\boldsymbol{C}_{n\times 4}$ is a mode shape function matrix, and $\boldsymbol{A} = \{A_1, A_2, A_3, A_4\}^{\mathrm{T}}$. When λ is determined, the least square solution of Eq. (5) gives

$$\boldsymbol{A} = (\boldsymbol{C}^{\mathrm{T}}\boldsymbol{C})^{-1}\boldsymbol{C}^{\mathrm{T}}\boldsymbol{Y}_k \tag{6}$$

Let
$$E = |\boldsymbol{Z}_k - \boldsymbol{Y}_k| = \sum_{i=1}^{n} (Z_k(i) - Y_k(i))^2 \tag{7}$$

where $\boldsymbol{Z}_k = \boldsymbol{C}(\boldsymbol{C}^{\mathrm{T}}\boldsymbol{C})^{-1}\boldsymbol{C}^{\mathrm{T}}\boldsymbol{Y}_k$. When Eq. (7) attains the minimum value, the optimum value of λ is derived. Substituting the optimum value of λ into Eq. (6), the optimum value of $\boldsymbol{A}$ and the optimum mode shape vector are obtained.

2 Application and Comparison

2.1 Description of the Runyang Bridge

The Runyang Yangtse River Bridge is one of the longest bridges in the world, including a suspension bridge and a cable-stayed bridge. The suspension bridge has an overall length of 2 430 m and a main span of 1 490 m. The bridge deck is a 31.0 m wide steel box structure. The two bridge towers are 215.58 m high made of pre-stressed reinforced concrete. The Runyang Cable-Stayed Bridge has an overall length of 756.8 m and a main span of 406.0 m. The bridge deck is a 37.4 m wide steel box structure. The two bridge towers are 146.888 m high made of pre-stressed reinforced concrete.

2.2 Structural health monitoring system(SHMS)

To have an online monitoring of performance and health status of the Runyang Yangtse River Bridge and to verify the design parameters in the design of the bridge, an SHMS was installed upon the bridge in 2005. The SHMS consists of the sensory system, the data acquisition system, the data communication and transmitting system, and the data processing and analysis system[1]. In the sensory system, there are different types of sensors, such as anemometers, a temperature measurement assembly, accelerometers, strain gauges, a level sense system, displacement transducers, and a global position system.

2.3 Operational modal identification system(OMIS)

Based on the SHMS, an operational modal identification system is put forward, which can be used to identify the modal parameters in a timely manner. The layout of sensors in the operational modal system is shown in Fig. 1. There are four sections on the main cables including eight lateral accelerometers and four vertical accelerometers. A total of 29 accelerometers are located at the nine sections of the bridge deck in the main span. A total of 12 accelerometers are installed in the north tower and the south tower, respectively, of the bridge. The total number of accelerometers is 53.

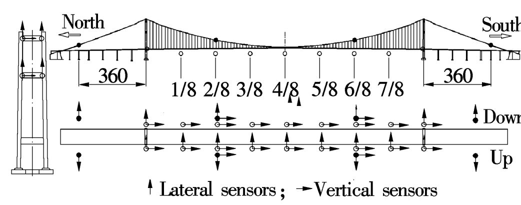

Fig. 1 Sensor layout of the operational modal system(unit: m)

2.4 Application

On May 1, 2005, the online modal identification system was successfully installed on the Runyang Suspension Bridge. It has been running more than three years now. As an example, the vibration response data recorded during the typhoon Matsa excitation on August 6, 2005 is used to illustrate the application program.

Fig. 2 shows the PSD of deck vertical vibration data collected at different sections. It can be seen that the PSD has a peak at a resonant frequency. Meanwhile, the PSD of response at the 7/8 section has lower frequency peaks than others. In order obtain as many resonant frequencies as possible, all the accelerometers response data recorded at different positions should be used, which can avoid the leakage of resonant frequencies. Fig. 3 and Fig. 4 show the ANPSD of vertical and lateral deck vibration data, respectively.

Fig. 5 shows the PSD sum of vertical acceleration measured at the 6/8 section of the cable. Fig. 6 shows the PSD of longitudinal acceleration measured at the top of the south tower. By comparing Fig. 5 with Fig. 3, most of the resonant peaks are similar. A similar observation can be made by the comparison of Fig. 6 and Fig. 3. Therefore, some of the vertical vibration of the deck is coupled with the cable and tower.

It is observed that the peak-picking method allows the identification of mostmodes, including the close frequencies. However, this method is efficient only in structures where different types of modes are independent and where the closely spaced modes are not of the same type(vertical bending, lateral bending, or torsion). Considering that most of modes of the suspension bridge are independent, the peak-picking method can be applied successfully. It is worth noting that the identified results from the deck, cable and tower achieve a very good correlation.

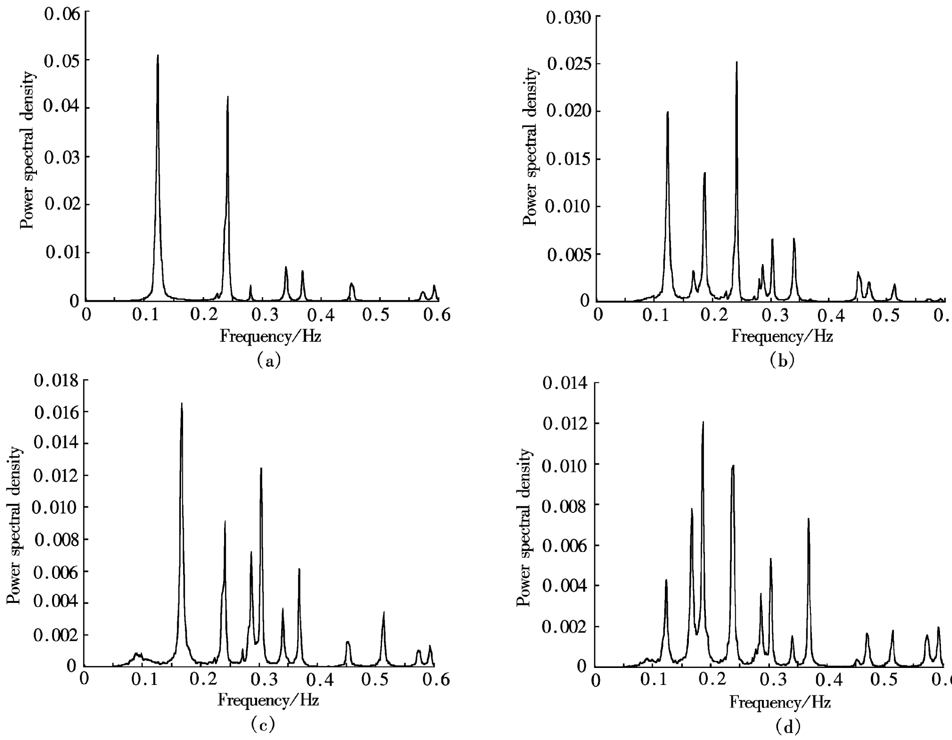

Fig. 2 PSD of deck vertical vibration data obtained from different sections. (a)4/8 section; (b)5/8 section; (c)6/8 section; (d)7/8 section

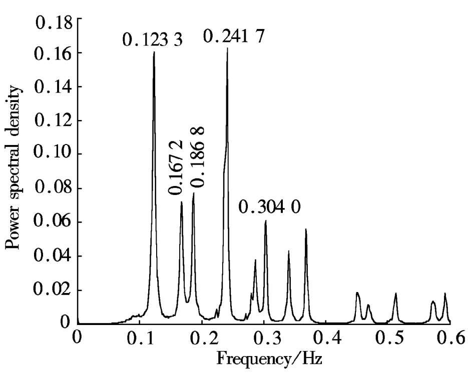

Fig. 3 ANPSD of deck vertical vibration data

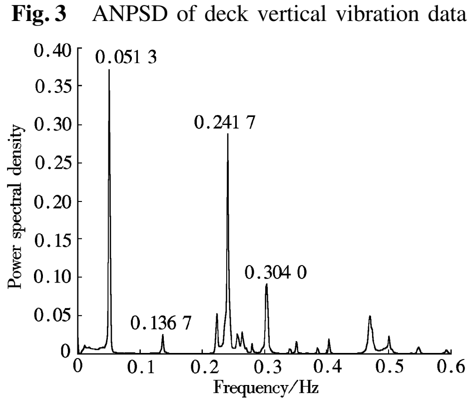

Fig. 4 ANPSD of deck lateral vibration data

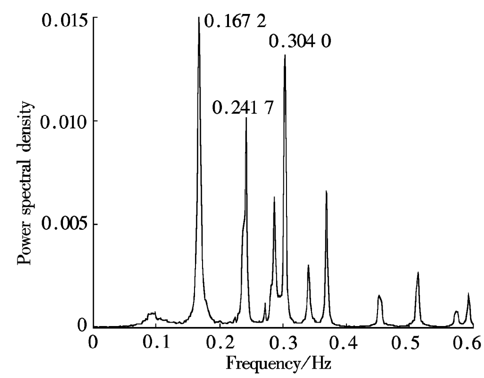

Fig. 5 PSD of vertical response of cable

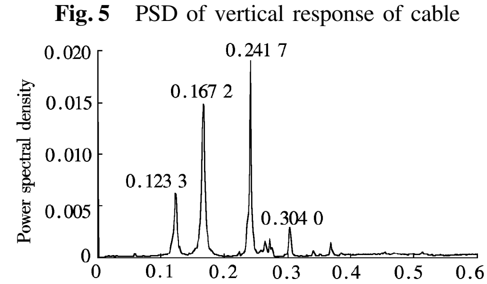

Fig. 6 PSD of longitudinal response of tower

2.5 Comparison

In order to verify the reliability of the operational modal identification system, the identification results are compared with those from the field measurements conducted in January 2005, which set 90 test points along the main deck of the bridge. Tab. 1 shows the results from the OMIS during typhoon Masta (referenced as OMIS-1) and the field measurement (FM). It is seen that most of the identification results from the two methods are close to each other. Fig. 7 shows the three tested bending vibration shapes of the deck. In addition, the results from the OMIS on August 4, 2005 (referenced as OMIS-2), before typhoon Masta approached, are also presented in Tab. 1. It is also noted that some modal frequencies identified from the OMIS, such as L1 and L2, have a decrease of about 15% compared with those from the FM.

Tab. 1 Comparison of modal parameters identified from OMIS and FM

Order	Frequency/Hz			Mode shape
	OMIS-1	OMIS-2	FM	
L1	0. 051 3	0. 051 3	0. 058 6	First symmetrical lateral bending
L2	0. 136 7	0. 140 4	0. 158 7	First unsymmetrical lateral bending
V1	0. 123 3	0. 122 1	0. 122 1	First symmetrical vertical bending
V2	0. 167 2	0. 167 2	0. 168 5	Second symmetrical vertical bending
V3	0. 186 8	0. 186 8	0. 188 0	Second unsymmetrical vertical bending
T1	0. 241 7	0. 241 7	0. 239 8	First symmetrical torsion
T2	0. 304 0	0. 305 2	0. 309 8	First unsymmetrical torsion

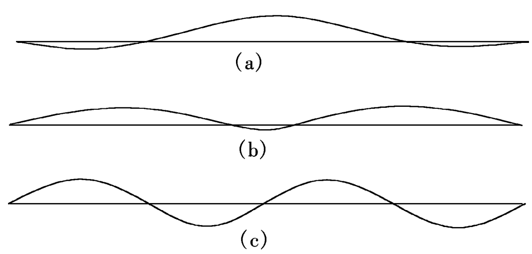

Fig. 7 Vertical bending vibration shapes of deck. (a) First symmetrical vertical bending(V1); (b) Second symmetrical vertical bending(V2); (c) Second asymmetrical vertical bending(V3)

3 Conclusion

In this paper, the operational modal identification system based on a SHMS is discussed. A novel mode shape optimum method is proposed. The output-only modal parameter identification of large span suspension bridges can be effectively carried out by a combination use of the peak-picking method and the cross spectrum method. As an example, the vibration response data of the deck, cable and tower recorded during typhoon Matsa excitation are used to illustrate the program application. The modal parameters identification results are compared with those from the field measurements. The results show that the identification results from the two methods are very close to each other. Moreover, it is essential to verify the identified results by using some other independent identification techniques due to the complexity of the problem. The application of supplementary techniques will increase the reliability of the identified results.

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基于结构健康监测系统的悬索桥运行模态识别

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摘要:介绍了联合应用峰值法和互谱法的模态参数识别方法,并提出了一种新的主梁振型优化方法.将上述方法应用于润扬大桥悬索桥的运行模态识别系统中,利用结构健康监测系统采集的振动响应数据获取结构的模态参数.作为应用实例,对台风麦莎作用下的主梁、主缆和桥塔振动响应数据进行了模态参数识别.结果表明:主梁部分振型的模态频率不仅能从主梁的振动响应识别出来,而且能够从主缆和桥塔振动响应中识别,主梁、主缆和桥塔之间存在较强的耦合振动.此外,将运行模态的识别结果和成桥之初的现场测试结果进行了对比,二者识别结果整体上吻合较好,但运行模态系统识别的部分振型模态频率,如 L1 和 L2,发生了较明显的下降.

关键词:悬索桥;运行模态识别;结构健康监测系统;环境振动测试

中图分类号:U441.3