Proc. of the 6th Intl. Symposium on Reliability Engineering and Risk Management (6ISRERM)
31 May – 1 June 2018, Singapore
Editor(s) Xudong Qian, Sze Dai Pang, Ghim Ping Raymond Ong, Kok-Kwang Phoon

INVESTIGATION ON THE DYANAMIC PROPERTIES OF A FOOTBRIDGE UNDER DIFFERENT LOADINGS

Jun HU[1] and Heung-Fai LAM[2]

[1]*Department of Architecture and Civil Engineering, City University, Hong Kong SAR, China*
E-mail: junhoo.19880203.whu@gmail.com

This paper presents the related works on ambient vibration test and modal identification of a campus footbridge during a Typhoon event. The footbridge is characterized as a typical steel truss system supported by two columns located at two sides of a dual-carriageway road and serves as a safety path between the main campus and the residence halls. The footbridge is very sensitive to the ambient vibration sources such as walking pedestrian and passing-by vehicles. Therefore, investigation on the vibration serviceability problem of the footbridge under various circumstances is necessary. Under a Typhoon event, the dynamic behaviour of the footbridge was explored by a four-setup ambient test carried out on the deck. As a comparison, another set of test was carried out under normal working condition with continuous pedestrian flow. To extract the modal parameters from the two sets of ambient vibration test data, the fast Bayesian FFT method was adopted. Based on the obtained measurement data, two sets of modal parameters were identified. The modal parameters under different vibration loadings were compared and discussed. It was found that a unique dynamic behaviour of the footbridge can be observed from the Typhoon induced vibrations.

Keywords: Ambient vibration test, Bayesian operational modal analysis.

1 Introduction

Footbridge can be characterized as typical steel-truss structures with the combination of light weight, slenderness and high performance. It is usually designed for very practical purpose and has fewer non-structural elements, which makes it cost-effective in construction and appealing from an architectural point of view. This kind of truss structures are usually very thin and present much less inherent damping and lower natural frequencies, therefore it is susceptible to human-induced vibration. Under the situation of external loads due to crowd and continuous pedestrian walking on, footbridge may suffer from excessive vibration that inhibits the normal walking and causes pedestrian discomfort. Although the excessive vibration may not affect the fatigue life or safety of the footbridges, the serviceability problem in terms of disturbing vibration really annoys the pedestrians. Advanced design methods make it reasonable to assume that footbridges have enough adequacy of in structural strength and reliability, and therefore serviceability is one of the main concerns in the design for this kind of structures. Gentile *et al.* (2008) studied the dynamic properties of a historic timber footbridge supported by two couples of cables after the retrofit. Ambient vibration measurements as well as geometric survey were carried out. Modal properties of the footbridge were extracted by the peak picking (PP) and the frequency domain decomposition (FDD) techniques from the ambient vibration data. Modal parameters obtained from the dynamic tests were used to update the structural model parameters of a finite element model of the footbridge. The results were used to evaluate the overall safety of the investigated footbridge under the service loads.

Since footbridge is usually functioned as a safety path for pedestrian and become indispensable in people's daily travel, special attention should be paid to the dynamic assessment of footbridge (Bachmann 1992; Fujino 1993). To assess the vibration serviceability of a footbridge, a reliable set of modal parameters identified from dynamic field test is needed (Lam *et al*. 2017; Hu *et al*. 2018). This paper presents the ambient vibration test and modal identification of a typical steel truss footbridge. It locates between the main campus and student residence. Since pedestrian flow on the footbridge during working day is large, it is of vital importance to explore the serviceability of the footbridge by assessing the dynamic behavior. Under a Typhoon event, the acceleration data of the footbridge was obtained by a four-setup ambient test carried out on the deck. Another set of test under normal working condition with continuous pedestrian flow was carried as a comparison. The modal parameters from the two scenarios were identified from the measured data. The identified modal parameters revealed that the dynamic properties of the footbridge vary under different ambient vibration loadings.

2 Ambient Vibration Test on Footbridge

The target footbridge (as shown in Figure 1(a)) is located between the main campus and student residence over a dual-carriageway road. The footbridge is a typical steel truss system and the dimension is about 15 meters long by 4 meters wide. Figure 2(b) shows the measurement plan on the bridge deck. To capture the dynamic properties of the footbridge, a total of 18 measurement points were planned on the bridge deck. It is clear that the dominant modes of the footbridge are in the vertical direction, thus only vertical vibration was considered in the measurement. With only six accelerometers are available, the measurement was divided into four setups. The schematic measurement plan is shown in Figure 1(b). The circled numbers in the figure indicate the sensor positions together with the sensor number (i.e., Sensor 1 to Sensor 6) on the bridge deck and the underlined numbers next to sensor positions indicate the corresponding setup numbers. Two reference sensors marked with R1 and R2 will not move at all during the measurement and the purpose is to combine the mode shape information from the individual setups to obtain the full mode shape. The remaining four sensors (i.e., sensors 3 to 6) will be moved to the corresponding measurement locations in each setup.

Figure 2(a) shows the six force-balance tri-axial accelerometers and a self-developed signal processing box used in the field test. In each setup, the sampling frequency was set at a relatively high value of 2048 Hz. Before the measurement, all the measurement channels were verified at first as shown in Figure 2(b). In each setup, 18 channels of acceleration signals were obtained.

(a)

(b)

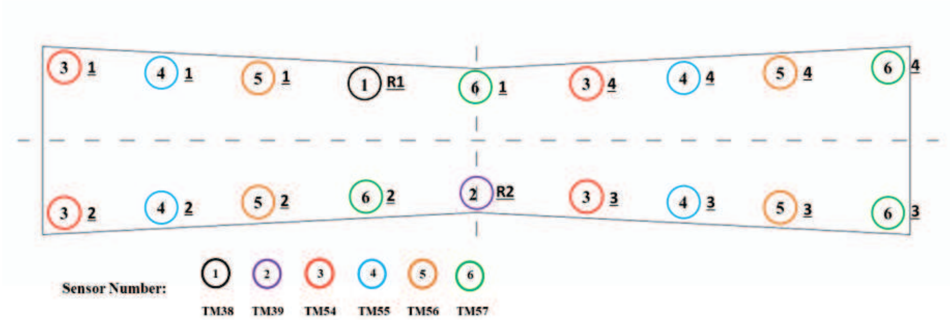


Figure 1: (a) Front view of the footbridge and (b) Measurement plan on the bridge deck.

(a) (b)

Figure 2: Equipment used in the test: (a) Six force-balance tri-axial accelerometer and self-developed signal processing box; (b) Channel verification and sensor calibration.

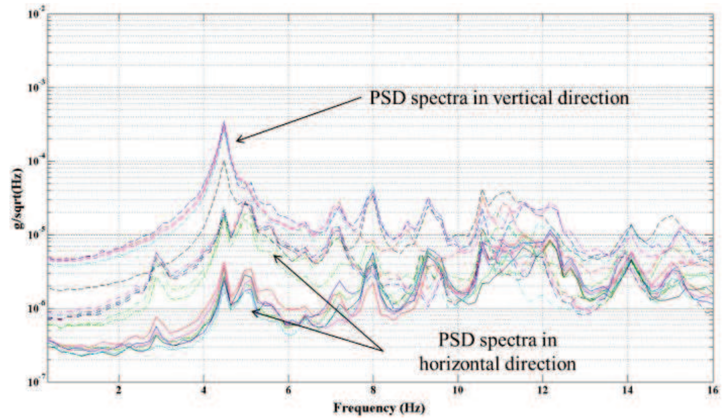
3 Experimental Case Study Results

3.1 *Modal Identification*

The fast Bayesian FFT method was adopted in this paper to extract the modal properties from the measured ambient vibration data. Due to the space limitation in this conference paper, interested readers are referred to Yuen *et al*. (2003) for original Bayesian FFT approach and to Au (2012a, 2012b and 2017) for a recently developed fast algorithm that makes full-scale ambient test applicable.

Figure 3(a) and 3(b) show the power spectral density (PSD) spectra from all channel of a typical set of data (setup 1) from a Typhoon event (Case 1) and a normal working condition (Case 2). For the Typhoon event, the maximum wind speed is 54km/h and the average wind speed is 35km/h. From the PSD spectra, it is obvious that the vibration in the vertical direction is dominant. The signal to noise ratio of Case 2 (i.e., the one under continuous pedestrian flow) is about 10 times larger than that of Case 1 at the frequency of 2 Hz. Five vertical modes were identified using fast Bayesian FFT method.

(a)



(b)

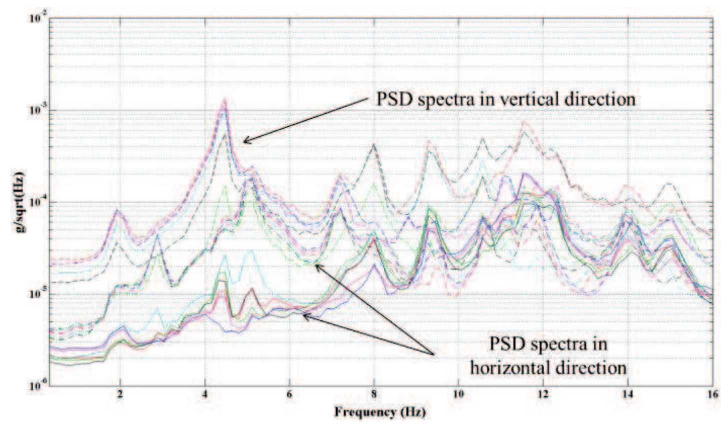


Figure 3: PSD spectra from all channels: (a) a Typhoon event and (b) normal working condition with continuous pedestrian flow.

3.2 *Experimental Results*

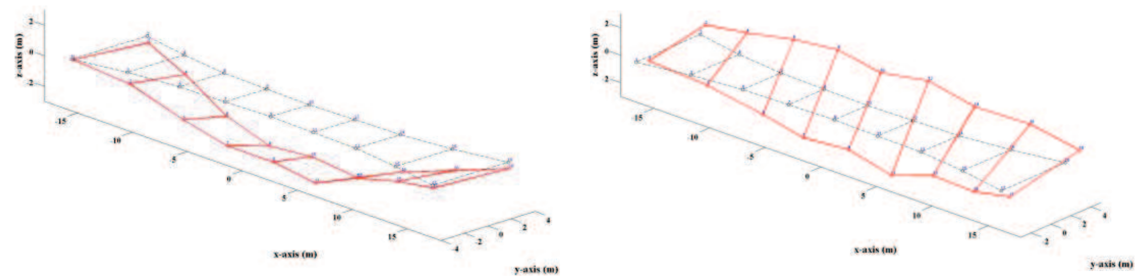
The identified natural frequencies and damping ratios of the five vertical modes are listed in Table 1 and the corresponding mode shapes are shown in Figures 4 to7. It is clear that the natural frequency of each mode is basically the same in the two cases. As for the damping ratios, it is clear that the values in Case 2 of each mode are larger than the corresponding one in Case 1.

Table 1: Natural frequencies and damping ratios of identified modes

Mode	1	2	3	4	5
Case 1	4.44(0.81%)	7.13(1.14%)	8.00(0.67%)	9.34(0.69%)	10.57(0.94%)
Case 2	4.41(1.27%)	7.22(1.54%)	7.94(0.80%)	9.38(0.85%)	10.53(1.13%)

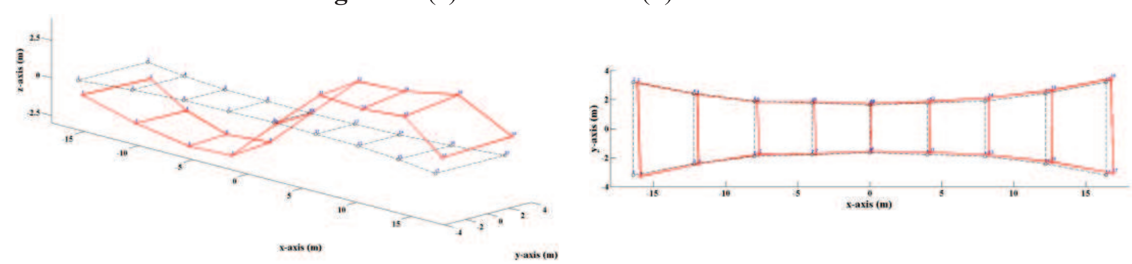
Due to the limitation of content, only the mode shapes from Case 1 are listed here, it should be noted that the mode shapes are basically the same in the two cases. The first vertical mode of the footbridge is around 4.4 Hz and is like a bending mode of the bridge deck (as shown in Figure 4(a)). The natural frequency of this mode is close to the fast walking step frequency of human. The second vertical mode of footbridge is around 7.1 Hz and it can be considered as the first torsional mode of the bridge deck (see Figure 4(b)).

Figures 5 and 6 show the third and fourth vertical mode of the footbridge, respectively. The natural frequencies are around 8.0 Hz and 9.3 Hz for these two modes, respectively. From PSD spectra, their peaks are clearly separated, but their vibration patterns appear to be the same as seen from Figures 5(a) and 6(a). By considering of their mode shape projection in the x-y plane in Figure 5(b) and 6(b), it is clear that that the two modes have different vibration pattern in the horizontal direction. The mode shape projection of mode 3 in horizontal direction is a translational mode along x-axis, as Mode 4, it is a rotational mode with the center of rigidity at somewhere in the middle of the bridge deck. Figure 7 shows the fifth vertical mode of the footbridge with a natural frequency around 10.5 Hz and it can be considered as the third bending mode of the bridge deck.



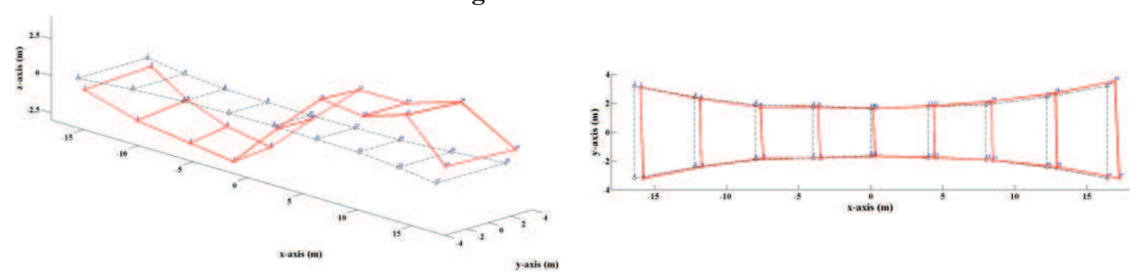
(a) (b)

Figure 4: (a) First mode and (b) Second mode.



(a) (b)

Figure 5: Third mode.



(a) (b)

Figure 6: Fourth mode.

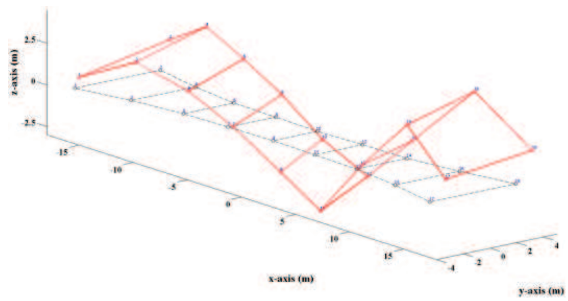


Figure 7: Fifth mode.

4 Conclusions

This paper presents the operational modal identification of a footbridge during a typhoon event. It is a typical steel truss structure and serves as a safety path between main campus and student residence. The slenderness of the footbridge makes it susceptible to human induced vibration during daytime. To assess the serviceability of the footbridge, dynamic field tests were carried out to identify the modal properties. The first measurement was carried out during a typhoon event and the second measurement was carried out in the normal working condition. In total, five vertical modes were identified using the measured data, including four bending modes and one torsional mode. Based on the identified modal parameter, it was found out that the damping ratio is most susceptible to different loading conditions.

Acknowledgements

The work was supported by the CityU Strategic Research Grant (Project No. CityU 11242716 (9042336)). The authors are thankful for the support.

References

Au, S. K. (2017). *Operational Modal Analysis: Modeling, Bayesian Inference, Uncertainty Laws*. Springer.

Au, Siu-Kui. "Fast Bayesian ambient modal identification in the frequency domain, Part I: Posterior most probable value." Mechanical Systems and Signal Processing 26 (2012a): 60-75.

Au, Siu-Kui. "Fast Bayesian ambient modal identification in the frequency domain, Part II: Posterior uncertainty." Mechanical Systems and Signal Processing 26 (2012b): 76-90.

Bachmann, H. (1992). Vibration upgrading of gymnasia, dance halls and footbridges. Structural Engineering International, 2(2), 118-124.

Fujino, Y., Pacheco, B. M., Nakamura, S. I., & Warnitchai, P. (1993). Synchronization of human walking observed during lateral vibration of a congested pedestrian bridge. Earthquake engineering & structural dynamics, 22(9), 741-758.

Gentile, C., & Gallino, N. (2008). Ambient vibration testing and structural evaluation of an historic suspension footbridge. Advances in Engineering Software, 39(4), 356-366.

Hu, J., Lam, H. F., & Yang, J. H. (2018). Operational modal identification and finite element model updating of a coupled building following Bayesian approach. Structural Control and Health Monitoring, 25(2).

Lam, H. F., Hu, J., & Yang, J. H. (2017). Bayesian operational modal analysis and Markov chain Monte Carlo-based model updating of a factory building. Engineering Structures, 132, 314-336.

Yuen, Ka-Veng, and Lambros Katafygiotis. "Bayesian fast Fourier transform approach for modal updating using ambient data." Advances in Structural Engineering, 6.2 (2003): 81-95.