Ambient Vibration Survey and Vibration Serviceability Evaluation on Footbridges

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Abstract—Altogether 37 footbridges were randomly chosen in Beijing metropolitan and ambient vibration surveys were carried out. The vertical fundamental frequencies are obtained by peak-picking technique based on frequency domain decomposition, the damping ratios are calculated by half-power bandwidth method. The fundamental frequencies are mostly in the range of 2-7 Hz, the damping ratios are mostly in the range of 0.2-0.8%. Combining Chinese industrial standard of Technical Specifications of Urban Pedestrian Overcrossing and Underpass and British bridge design code of BS 5400, the vibration serviceability is evaluated. The results show that the footbridges with fundamental frequencies lower than 3 Hz cannot satisfy vibration serviceability requirements, the footbridges with fundamental frequencies at 3-5 Hz can generally meet the demand of peak acceleration limits given in BS 5400, but a certain footbridge responds excessively, the footbridges with fundamental frequencies higher than 5 Hz can easily meet vibration serviceability requirements. The results of dynamic parameters and vibration serviceability evaluation of footbridges can give some help for footbridge design practice.

Keywords-footbridge; fundamental frequency; damping ratio; vibration serviceability; evaluation

I. INTRODUCTION

In recent years, as one sort of spatial transportations, footbridges have been widely used in urban construction. With the use of high-strength lightweight materials as well as the improvement of aesthetic requirements, footbridges are tending to become lighter and more slender. Meanwhile, owing to the decrease of natural frequencies and damping, footbridge natural frequencies are close to the sensitive range of pedestrian normal walking, causing excessive vibrations which can make people uncomfortable or even panic, namely footbridge vibration serviceability [1-4]. Hence the natural frequencies and damping are the important controllable factors which should be considered in footbridge design.

To this end 37 footbridges are randomly chosen in Beijing metropolitan in this paper. Ambient vibration surveys are conducted on them. By means of peak-picking technique based on frequency domain decomposition and half-power bandwidth method, the vertical fundamental frequencies and damping ratios are identified quickly. Then vibration serviceability is evaluated on them based on domestic and foreign serviceability standards, in the end some advice is given.

II. TESTING METHOD AND PRINCIPLE

Ambient vibration survey (AVS) is one way to obtain structural dynamic parameters using ambient excitation, where ambient excitation refers to the loads imposed on structures which are resulted from wind, pedestrians and vehicles together with their combination in natural environment. Due to the large size and complex structure of footbridge, the traditional artificial excitation cannot be applied effectively. Moreover, the exciting equipment is expensive and it may cause damage to the structure. The ambient vibration test method is a simple and quick as well as low-cost and safe approach which does not affect the normal use of structure [5-6]. Hence ambient vibration test method is adopted.

The peak-picking technique is one way of dynamic parameters identification in the frequency domain, which regards the frequency corresponding to the peak point of frequency response function (FRF) as the natural frequency of structure. When the FRF cannot be acquired due to unknown excitation, the auto power spectrum density function of structural response is used. The peak-picking technique based on frequency domain decomposition is simple and fast, which has some anti-noise ability and is a shortcut way to confirm the low order modes. The principle of peak-picking technique based on frequency domain decomposition is described briefly as follows [7].

For the *n*-degree-of-freedom linear system with Rayleigh damping, the vibration differential equation is expressed as

$$\mathbf{M}\ddot{\mathbf{y}}(t)+\mathbf{C}\dot{\mathbf{y}}(t)+\mathbf{K}\mathbf{y}(t)=\mathbf{b}\mathbf{u}(t). \tag{1}$$

where $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ are the mass, damping and stiffness matrices respectively, **b** and **u** are the excitation position and time-history matrices respectively. By the mode superposition method (1) is solved, where $2n$ complex con-eigenvalues λ_i , λ_i^* as well as $2n$ complex con-eigenvectors ψ_i , ψ_i^* are obtained, here

$$\lambda_i, \lambda_i^* = -\zeta_i \omega_i \pm j\omega_i \sqrt{1-\zeta_i^2} \quad . \quad (2)$$

where ω_i is the natural frequency, ζ_i is the modal damping ratio.

The mode decomposition of the power spectrum matrix of $\mathbf{y}(t)$ is

$$S_{yy}(\omega) = \left[\sum_{i=1}^{n}\left(\frac{1}{a_i}\frac{\psi_i\psi_i^T}{j\omega-\lambda_i} + \frac{1}{a_i^*}\frac{\omega_i^*\psi_i^{*T}}{j\omega-\lambda_i^*}\right)\right] S_{uu} \left[\sum_{i=1}^{n}\left(\frac{1}{a_i}\frac{\psi_i\psi_i^T}{j\omega-\lambda_i} + \frac{1}{a_i^*}\frac{\psi_i^*\psi_i^{*T}}{j\omega-\lambda_i^*}\right)\right]^H . \quad (3)$$

where S_{uu} is the auto power spectrum matrix of excitation, a_i , a_i^* are the constants relying on i .

From (2) and (3) it is known that S_{yy} obtains the extremum at natural frequency ω_i , and it approximately equals

$$S_{yy}(\omega_i) = \left(\frac{1}{a_i}\frac{\psi_i\psi_i^T}{\zeta_i\omega_i}\right) S_{uu} \left(\frac{1}{a_i}\frac{\psi_i\psi_i^T}{\zeta_i\omega_i}\right)^H . \quad (4)$$

By utilizing singular value decomposition (4) becomes

$$S_{yy}(\omega_i) = \alpha_i \psi_i \psi_i^H . \quad (5)$$

where $\alpha_i = \frac{1}{(\zeta_i\omega_i)^2}\frac{1}{a_i a_i^*}\psi_i^T S_{uu}\psi_i^*$. Obviously at natural frequency ω_i each column (or row) of the power spectrum matrix S_{yy} can be regarded as the estimation of mode shape ψ_i , therefore before and after ω_i , there are $\omega = \omega_a$, ω_b corresponding to $1/\sqrt{2}$ of the peak amplitude, the modal damping ratio is given by

$$\zeta_i = \frac{\omega_b - \omega_a}{2\omega_i} . \quad (6)$$

III. AMBIENT VIBRATION SURVEYS ON FOOTBRIDGES

In total 37 footbridges are randomly chosen and numbered, which are located in Haidian district, Chaoyang district, Xicheng district and Dongcheng district, Beijing. The candidate footbridges cover the structural forms of single-span, multi-span and X type, with the maximum span of 120 m and the minimum span of 20 m. Except for the full steel truss bridges of Footbridges (abbreviated as Fs) 29, 32 and 34, most of them are steel box girder footbridges with concrete piers. Fig. 1 is the general view of F 1, which is a single-span steel box girder footbridge crossing street.

Figure 1. General view of F 1.

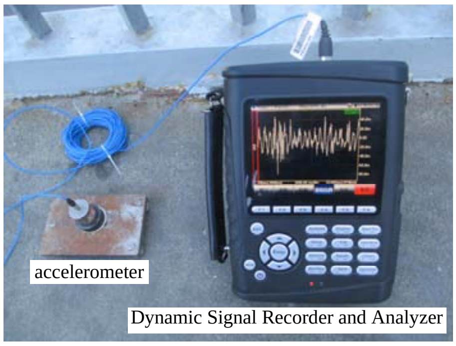

Figure 2. Test instruments for AVS

The test instruments consist of American CoCo-80 Dynamic Signal Recorder and Analyzer and a PCB 393B04 piezoelectric accelerometer. The Dynamic Signal Recorder and Analyzer with 8 input channels is easy to take and can record response signals instantly. The accelerometer with sensitivity of 1000 mV/g works in the frequency range of 0.25-750 Hz. In the experiment, the accelerometer is placed vertically in the midspan of footbridge. The sampling frequency is set as 25 Hz and the recording time is 82 s. Each footbridge is tested every other hour and altogether 3-5 tests are conducted. Fig. 2 is a picture of experimental test.

The acceleration time histories are decomposed by 2048 points fast Fourier transform using Hanning window function, and the auto power spectrum density is obtained. Then the fundamental frequency is recognized by peak-picking technique and the damping ratio is calculated by half-power bandwidth method. The ultimate fundamental frequency and damping ratio are determined by averaging the results of several tests, respectively. The vertical acceleration time histories of midspan of F 1 are shown in Fig. 3, and its corresponding auto power spectrum density curve is shown in

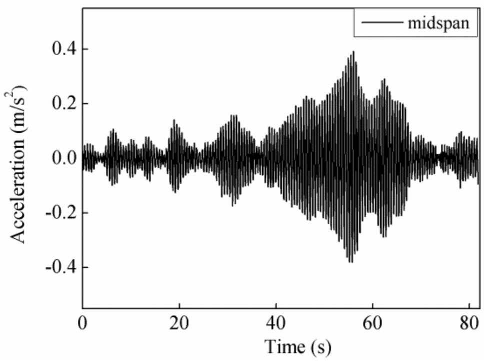

Figure 3. Acceleration time histories of F 1.

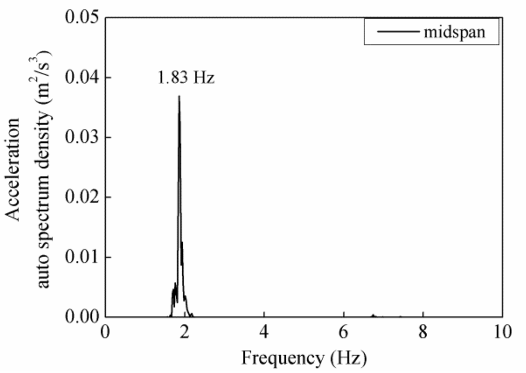

Figure 4. Acceleration auto spectrum density curve of F 1.

Fig. 4. It can be seen that the frequency identification is good and the fundamental frequency of F 1 is 1.83 Hz.

The fundamental frequencies of the 37 footbridges are summarized in Fig. 5, where the abscissa is footbridge number. It can be seen that most of the footbridges (34/37) have fundamental frequencies in the range of 2-7 Hz, with the mean fundamental frequency of 4.55 Hz and standard deviation of 1.52 Hz. Among them Fs 1 and 2 have the lowest fundamental frequencies (1.83 and 2.03 Hz respectively), which are both single-span pre-arched footbridges spanning over 30 m, while Fs 36 and 37 have the highest fundamental frequencies (7.32 and 8.47 Hz respectively), which are not so long but with many piers.

The damping ratios are scattered in Fig. 6, where they are about 0.2-0.8%, with the mean damping ratio of 0.50% and standard deviation of 0.20%. It is interesting to note that F 6 has the maximum damping ratio (1.22%) because it has been built for ages with lots of concrete. The dynamic parameters of each footbridge are listed in TABLE I. The damping ratios are slightly smaller than the values proposed by Bachmann [8]. With 90% probability of nonexceedance, the footbridge damping ratio is usually no more than

$$\zeta_{90\%} = \frac{1}{100}\left(1.13 - 0.105 f\right) \times 100\% . \tag{7}$$

where f is the fundamental frequency.

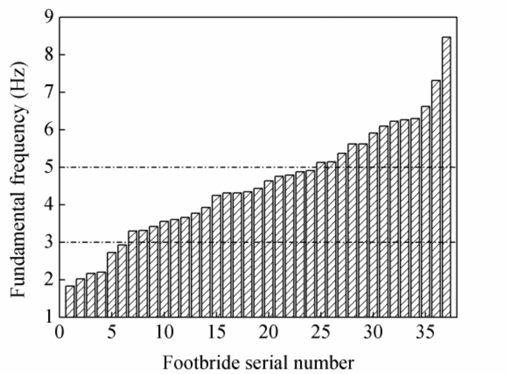

Figure 5. Histogram of fundamental frequencies.

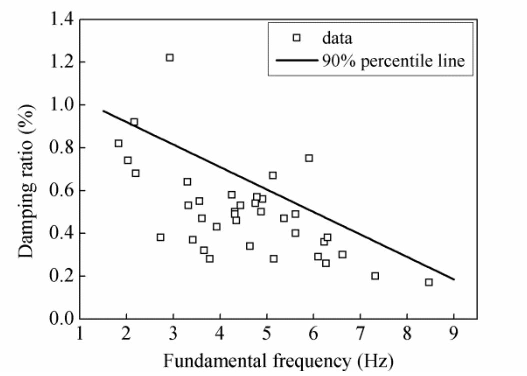

Figure 6. Dependence between damping ratio and fundamental frequency.

IV. VIBRATION SERVICEABILITY EVALUATION

At present there are two ways to ensure footbridge vibration serviceability, which are frequency adjusting method and dynamic response limiting method. The representative footbridge standards include British bridge design code BS 5400 [9], German footbridge design guideline EN03 [10], European Euro code EN 1990, International Standards Organization ISO 10137 and Chinese industrial standard CJJ69-95 (Technical Specifications of Urban Pedestrian Overcrossing and Underpass) [11]. For example, CJJ69-95 states that the vertical fundamental frequency of footbridge should not be less than 3 Hz. BS 5400 rules that if the vertical fundamental frequency of footbridge is greater than 5 Hz, vibration serviceability requirements are naturally satisfied, if it is between 1.5 and 5 Hz, the peak acceleration of structural response needs to be checked, i.e. the vertical maximum acceleration at any position of the bridge deck should be no more than

$$a_{\max} \le 0.5\sqrt{f} . \tag{8}$$

In order to make the evaluation simple and convenient, combining Chinese industrial standard CJJ69-95 with BS 5400, the evaluation methodology proposed in this paper is elaborated hereunder. The footbridge with fundamental frequency less than 3 Hz does not meet vibration serviceability requirements, the footbridge with fundamental frequency more than 5 Hz naturally satisfies vibration serviceability

TABLE I. FOOTBRIDGE DYNAMIC PARAMETERS AND SERVICEABILITY EVALUATION

Footbridge number	**Fundamental frequency (Hz)**	**Damping ratio (%)**	**Peak acceleration (m/s^2)**	**BS 5400 limit (m/s^2)**	**Evaluation result**
1	1.83	0.82	0.39	0.68	N
2	2.03	0.74	0.77	0.71	N
3	2.17	0.92	0.85	0.74	N
4	2.20	0.68	0.45	0.74	N
5	2.73	0.38	0.69	0.83	N
6	2.93	1.22	0.49	0.86	N
7	3.30	0.64	0.31	0.91	LS
8	3.32	0.53	0.22	0.91	LS
9	3.42	0.37	0.89	0.92	LS
10	3.56	0.55	0.19	0.94	LS
11	3.61	0.47	0.62	0.95	LS
12	3.66	0.32	0.27	0.96	LS
13	3.78	0.28	1.11	0.97	LN
14	3.93	0.43	0.33	0.99	LS
15	4.25	0.58	0.24	1.03	LS
16	4.32	0.50	0.51	1.04	LS
17	4.32	0.49	0.24	1.04	LS
18	4.35	0.46	0.60	1.04	LS
19	4.44	0.53	0.32	1.05	LS
20	4.64	0.34	0.30	1.08	LS
21	4.76	0.54	0.46	1.09	LS
22	4.79	0.57	0.36	1.09	LS
23	4.88	0.50	0.64	1.10	LS
24	4.91	0.56	0.22	1.11	LS
25	5.13	0.67	0.49	—	S
26	5.15	0.28	0.61	—	S
27	5.37	0.47	0.35	—	S
28	5.62	0.40	0.58	—	S
29	5.62	0.49	0.24	—	S
30	5.91	0.75	0.28	—	S
31	6.1	0.29	0.19	—	S
32	6.23	0.36	0.30	—	S
33	6.27	0.26	0.18	—	S
34	6.30	0.38	0.12	—	S
35	6.62	0.30	0.13	—	S
36	7.32	0.20	0.09	—	S
37	8.47	0.17	0.14	—	S

Note: S denotes satisfied, similarly, N for not satisfied, LS for limit satisfied，LN for limit not satisfied.

requirements, while the footbridge with fundamental frequency at 3-5 Hz should be checked by the peak acceleration limit i.e. (8). Based on the measured vertical acceleration of structural response, the vibration serviceability of 37 footbridges is evaluated based on the above methodology. The detailed results are listed in TABLE I.

From TABLE I it is known that Fs 1-6 have fundamental frequencies lower than 3 Hz, part of them (Fs 1 and 4-6) satisfy the need of peak acceleration limits, however, they are against the rule with respect to fundamental frequency given in CJJ69-95, so they cannot meet vibration serviceability requirements. During in-situ tests the footbridges oscillate drastically even when only a few pedestrians pass through, discomfort is brought about, indicating their bad services. Fs 7-24 have fundamental frequencies at 3-5 Hz, most of them can meet the demand of peak acceleration limits, nevertheless, F 13 reacts fiercely, analysis shows that it covers a large span with wide deck, but yet column piers are used, resulting in low stiffness and damping parameters. Fs 25-37 with fundamental frequencies higher than 5 Hz can easily meet vibration serviceability requirements. It is worth mentioning that although Fs 29, 32 and 34 are all made of steel, reinforcement structures are designed in their side and top parts, additionally several pairs of column piers are built, the stiffness and damping are enlarged.

It has to be clear that due to testing restrictions the vibration serviceability of footbridges is surveyed under the regular service condition i.e. the pedestrian traffic class TC 2 [10], where single pedestrians can freely choose pace. In some extreme cases such as large commercial activities, the serviceability results need to be investigated further.

V. CONCLUSIONS

1) The fundamental frequencies of footbridges in Beijing urban districts are mostly in the range of 2-7 Hz with the mean fundamental frequency of 4.55 Hz, the damping ratios are mostly in the range of 0.2-0.8% with the mean damping ratio of 0.50%.

2) The footbridges with fundamental frequencies under 3 Hz violate the rule of Chinese national standard Technical Specifications of Urban Pedestrian Overcrossing and Underpass, so they cannot meet vibration serviceability requirements. The footbridges with fundamental frequencies between 3 and 5 Hz generally meet the demand of peak acceleration limits given in BS 5400, except that one certain footbridge responds excessively. The footbridges with fundamental frequencies

3) higher than 5 Hz easily meet vibration serviceability requirements.
4) Fs 1-6 with too low fundamental frequencies are suggested to mount reinforcement structures to improve their stiffness properties. F 13 with very low damping is suggested to install vibration absorbers such as viscous dampers or tuned mass dampers.
5) In footbridge design, if possible, it is recommended that the bridge span be decreased or the ratio of main span to side span be adjusted, which can raise the natural frequencies so as to avoid the sensitive frequency range of people walking.

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