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Field Measurements of the New CCTV Tower in Beijing

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Abstract

The emergence of a growing number of tall buildings, often with unusual shapes and innovative structural systems, has led to the realization of the need for and the importance of field measurements. The new China Central Television (CCTV) Tower in Beijing is one of tall buildings with a highly unusual shape and a complex structural system, requiring field measurements to identify its dynamic characteristics for the subsequent dynamic analysis of the tower under wind excitation, seismic-induced ground motion and traffic-induced ground motion. The structural system and the finite element model of the CCTV Tower are first introduced in this paper. The computed natural frequencies and mode shapes are then presented as a reference for the field measurement. After introducing the arrangement of the ambient vibration measurement, the field measured natural frequencies and damping ratios of the CCTV Tower are presented and the measured natural frequencies are finally compared with the computed ones. It was found that the structural damping ratios of the CCTV Tower are small and the computed natural frequencies are smaller than the measured ones by about 12~17%.

Keywords: Field measurement, The new CCTV Tower, Dynamic characteristics, Identification, Finite element analysis

1. Introduction

Extremely high population concentrations and growing social and commercial activities but limited available lands lead to many tall buildings emerging in urban areas. Some of these tall buildings are of unusual shapes and constructed with new materials and innovative structural systems. The finite element model and the subsequently computed dynamic characteristics of the buildings need to be verified or updated against field measurement results (Davenport, 1975; Isyumov, 1999; Kareem, 2003; Tamura, 2003). The new China Central Television (CCTV) Tower in Beijing is a 234 m tall building with a highly irregular shape and a complex structural system. Field measurement is thus required to identify its dynamic characteristics for the subsequent dynamic analysis of the tower under wind excitation, seismic-induced ground motion and traffic-induced ground motion.

Nevertheless, the field measurement of a large and complicated tall building is not an easy task (Litter and Ellis, 1995; Xu and Zhan, 2001). Careful measurement plan shall be set up with reference to the initial finite element results obtained from the design stage. A variety of sensors are applicable for field measurements of a tall building. The selection of the number and type of sensors is generally a compromise of many factors, such as budget, application objectives, site conditions, measurement duration, and operator's experience (Ewins, 2000). The sensors selected are then connected to the data acquisition system through hard-wire or optical fibre connections. Attention should be paid to the cable length because long cables may attenuate data signals, particularly high frequency signals, and the signals may be polluted by noise sources near the cable path.

This paper first introduces the structural system and the finite element model of the CCTV Tower. The computed natural frequencies and mode shapes are then presented as a reference for the arrangement of field measurement. After introducing the arrangement of the ambient vibration measurement, the field measured natural frequencies and damping ratios of the CCTV Tower are presented and the correlations of the acceleration responses of the building foundation with those of the superstructure of the building are investigated. The measured natural frequencies are finally compared with the computed counterparts.

2. Structural System and FE Model of the CCTV Tower

2.1. Structural system

As one of the modern wonders of Beijing, the new CCTV Tower is a special tall building in the Beijing central business district. The new CCTV Tower combines administrative functions with news, broadcasting, studios and programme production. It stands at 234 meters tall and has 54 floors. The building is formed by two leaning

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Figure 1. The new CCTV Tower in Beijing.

towers, bent 90° at the top and bottom to form a continuous tube. It measures 163 m long and 163 m wide at the foundation level, and 116 m by 112 m at the roof level. The cantilever part of the building connecting the two towers has 14 floors and the podium part of the building linking the two towers has 9 floors. As a result, its shape is highly unusual, as shown in Fig. 1. The structural system of the new CCTV Tower is also very complicated. It is a loop of six horizontal and vertical sections covering a large floor space and creating an irregular grid on the building's facade with an open centre. The primary support is achieved through the irregular grid on its surface, providing a visible expression of the forces travelling through the tube structure. The braced tube structure also gives the building the required robustness to withstand the likely seismic events in the area and therefore provides an extra level of safety. It is a real structural challenge, especially in consideration of wind and seismic resistant design.

2.2. Finite element model

The structural system of the new CCTV Tower is modelled using commercial software SAP2000. The isometric view of the finite element model is shown in Fig. 2.

The finite element model of the CCTV Tower includes 17,294 nodes, 56,302 frame elements and 10,689 shell elements. Floors and roof are modelled with shell elements, and other components with beam elements. The inclined braces are made of steel with Young's modulus of 206 GPa. The podium floors are made of reinforced concrete C40 (Chinese standard, characteristic cube strength = 19.1 MPa and Young's modulus = 32.5 GPa), and the upper floors are made of reinforced concrete C30 (characteristic cube strength = 14.3 MPa, Young's modulus = 30 GPa). The supportive joints at the foundation floor are restrained in three translation directions, whereas the rotational degrees of freedom are not restrained. The building weighs about 155,500 ton in total.

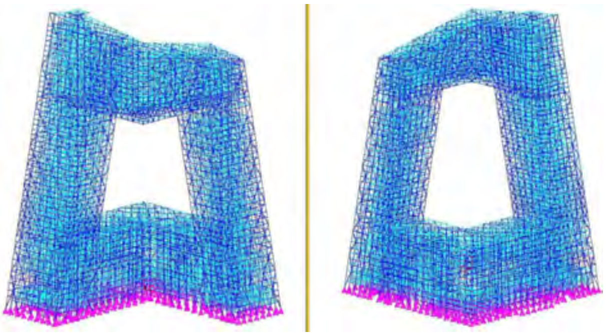
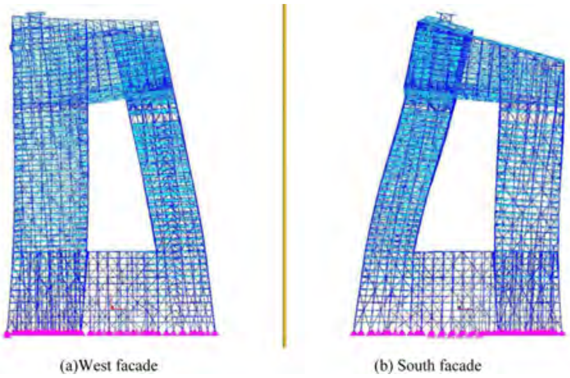


Figure 2. Isometric view of the FE model.

3. Computed Natural Frequencies and Mode Shapes

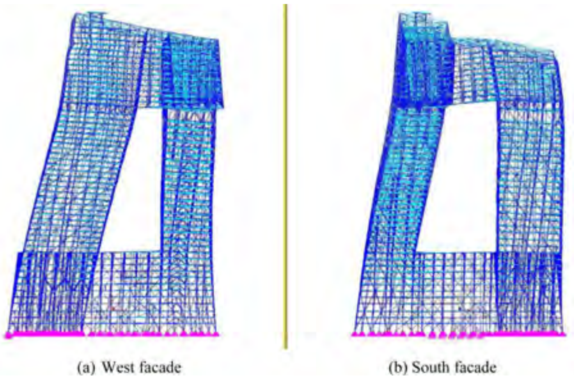
The first several modes of vibration of the CCTV Tower are computed through the eigenvalue analysis. Because of the complex structural system, the mode shapes of the building are three-dimensional in general. The first mode of vibration is mainly a lateral mode with a natural frequency of 0.278 Hz, in which the two leaning towers are bent. The west and south views of the first mode shape are shown in Fig. 3.

Because the new CCTV Tower is a truly three-dimensional structure, the second mode of vibration is also mainly a bending model with a natural frequency of 0.367 Hz, as shown in Fig. 4. The second mode, however, exhi-



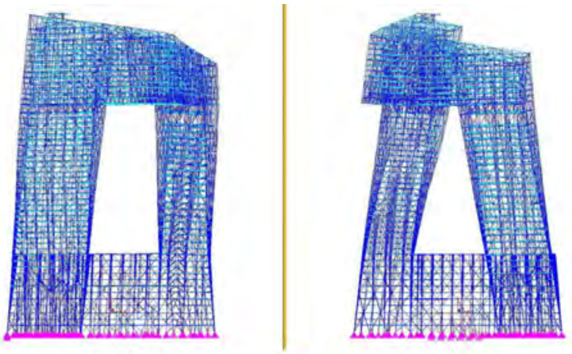
(a)West facade (b) South facade

Figure 3. The first bending mode.



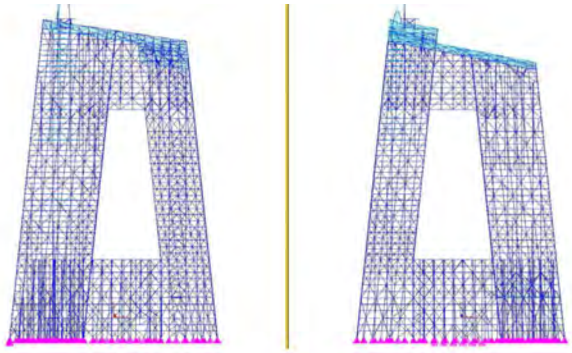
(a) West facade (b) South facade

Figure 4. The second bending mode.



(a) West facade (b) South facade

Figure 5. The first torsion mode.



(a)West facade (b) South facade

Figure 6. The first vertical mode.

bits some local bending of the cantilever part of the tower in the top south (see Fig. 4(b)). The third mode is a torsion one, and the corresponding frequency is 0.451 Hz. It can be seen from Fig. 5 that the two leaning towers plus the cantilever part of the building are rotated. The first vertical mode is shown in Fig. 6 with a natural frequency of 0.824 Hz, in which the top floors have clear vertical displacements.

4. Arrangement of Field Measurement

4.1. Ambient vibration measurement

At the design stage, the natural frequencies and mode shapes of a tall building are usually determined using the finite element technique whilst the modal damping ratios are often estimated based on the designer's experience. However, the accurate estimation of dynamic characteristics of a tall building is not a simple task at the design stage because, for instance, it is difficult to accurately estimate the stiffness contribution of non-structural elements to the natural frequencies and it is also intractable to numerically quantify the modal damping ratio of a complex structural system. The inaccuracy in damping and stiffness estimation may cause significantly adverse effects on the prediction of wind-induced dynamic response of the tall buildings. The identification of dynamic characteristics of tall buildings through field measurements is thus paramount for improving estimation accuracy.

The method for identifying dynamic characteristics of a tall building from the measured structural response depends on the testing method. Forced and ambient vibration test methods are two commonly used methods (Litter and Ellis, 1995). In the forced vibration test, the exciter is placed in a tall building at a suitable location and orientation for the excitation of that building in the mode to be investigated. The exciter is set to produce a known force and the exciting frequency is then incremented over the required frequency range, whilst the sensors are used to record the building response. The measured building response normalized with the input force against frequency is termed the frequency response function or transfer function, from which the natural frequencies and damping ratios of the building are identified using curve-fitting methods (Ewins, 2000). The mode shapes of the building can also be determined by setting the exciter to provide a steady state motion at a specified natural frequency and by monitoring the building responses at various locations along the building height. Ambient vibration of a tall building is supposed to be induced by wind, traffic waves and other nearby environmental disturbances under normal conditions. In this case, the simplest and convenient technique for identifying dynamic characteristics is peak-picking (Bendat and Piersol, 1986), which extracts the resonant peak frequencies in the spectrum and determines the damping ratio by the half-power bandwidth method. More advanced techniques, such as random decrement technique (Isyumoy, 1999), eigensystem realization algorithm (Juang and Pappa, 1985), and stochastic subspace identification (Van Overschee and De Moor, 1996), are also commonly used in practice. Most of these techniques assume that the unknown input is a white noise process and consequently the cross-correlation between the responses and the fixed reference point (s) can be treated as free responses (James et al., 1995). For large-scale civil structures, the forced vibration test method is usually difficult or prohibited because it requires the huge exciter to provide sufficient force, which may cause damage to the building. Moreover, the operation or construction of the building has to be shut down during the forced vibration test. Therefore, the ambient vibration test method is the sole and natural choice, and is used in this investigation.

4.2. Measurement arrangement

The computed mode shapes of the new CCTV Tower indicate that it is very difficult, both technically and economically, to accurately measure the mode shapes of the tower. It was decided to measure the first a few natural frequencies and modal damping ratios of the tower only in this study. After a careful observation of the computed mode shapes, the measurement points were arranged on the 37th floor with the measurement points of 11, 13, 14 and 15, and on the 48th floor with the measurement point of 12 (see Fig. 7). Furthermore, the vibrations of the buil-

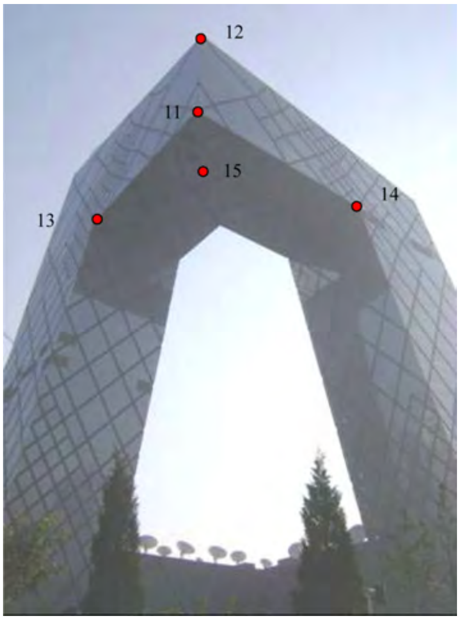


Figure 7. Measurement points on 37th and 48th floors.

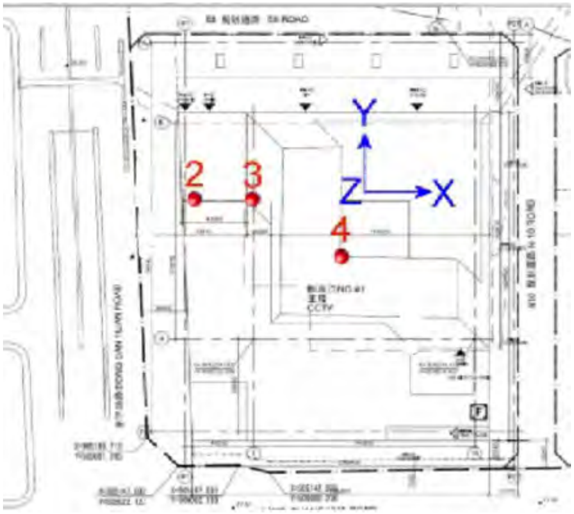


Figure 8. Measurement points on basement.

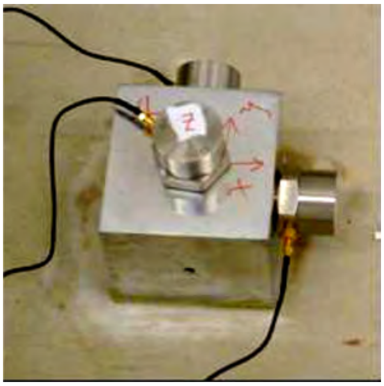


Figure 9. Accelerometers in x, y and z directions.

Figure 10. Calibration test.

ding foundation were also measured at the measurement points 2, 3 and 4, as shown in Fig. 8, so that they could be compared with the vibration of the superstructure at the 37th and 48th floors. Except the measurement point 15, at which the acceleration was measured in the vertical direction only, the acceleration responses at all other points were measured in the x (east), y (north) and z (vertical) directions.

Because the size of the new CCTV Tower is huge and the distances between the measurement points of the superstructure and those of the foundation are very long, it was decided to use two recording data stations: one located on the 37th floor and the other on the 3rd basement floor. A long cable was then used to connect the computers at the two recording station with a trigger. By pressing the button on the trigger, a voltage pulse could be generated and the two stations were then triggered by this pulse to start sampling data synchronously. In this way, the lengths of measurement cables and accordingly the adverse noise effects could be reduced significantly.

The first a few natural frequencies of the new CCTV Tower are relatively low and the acceleration responses of the building, particularly the tower foundation, under ambient excitation are very small. The accelerometers used in the measurement should be sensitive enough and should be able to catch the low frequency components. To this end, the accelerometers of type CA-YD-109B were adopted (see Fig. 9). Its sensitivity is about 2500 pC/g and its low frequency limit is 0.2 Hz which is lower than the first natural frequency of the building. The charge amplifiers KD5008C were used to match with the accelerometers. Even using the two recording stations, the distances between the measurement points and the data recording station were still quite long with the distance more than 100 meters. In order to reduce the influence of electromagnetic noise as far as possible and to increase the signal-to-noise ratio of the recorded data as high as possible, the signals recorded by the accelerometers were amplified before transmitted to the distant station for recording. Before the formal measurement, the calibration tests were performed for each channel including the accelerometer, the amplifier, the shielded cable and the recorder by using a calibrator of model 699A02 as shown in Fig. 10. This calibration work is important for the measurement accuracy of dynamic responses. The recorded time histories of acceleration responses were finally used to analyze the response spectra and coherence functions and to identify the dynamic characteristics of the building.

5. Measurement Results and Comparison

5.1. Time histories and auto-spectrum

The ambient vibration measurement of the new CCTV Tower was carried out in July 2012 after the building was completed. The measurements were carried out 3 times and each lasted for 2 hours. It is important to select the stationary data for the identification of dynamic characteristics of the building. To this end, the recorded data which are stationary for all channels were selected for further analysis. Before analysis, the data were filtered by a low pass filter. The upper frequency limit of the low pass filter was set to 40 Hz in consideration of the vibration of the building foundation. Figures 11 and 12 show the time histories and the auto-spectral density of the acceleration responses selected from the measurement points 2 and 11 in the x-direction. The Fourier transformation and the auto-spectrum of a response time history $x(t)$ are given by

$$F_x(\omega) = \int_{-\infty}^{+\infty} x(t) e^{-i\omega t} dt \tag{1}$$

$$S_{xx}(\omega) = \lim_{T \to \infty} \frac{1}{2T} |F_x(\omega, T)|^2 \tag{2}$$

It can be seen from Figs. 11 and 12 that both the time history and the auto-spectrum of the acceleration response at the measurement point 2 on the 3rd basement are quite different from those at the measurement point 11 on the 37th floor. The vibration of the building foundation was mainly caused by the ground motion due to traffic (both railway and highway) nearby, whereas the dynamic response of the building at the 37th floor was mainly the modal responses of the building itself. In particular, the foundation vibration energy distributes over a relatively wider frequency range, while the 37th floor response exhibits the dominate peaks at several natural frequencies of the building.

5.2 Cross-spectrum and coherence function

Assume that there are the two response time histories $x(t)$ and $y(t)$, $-\infty < t < +\infty$. Their Fourier transformations are given by

$$F_x(\omega) = \int_{-\infty}^{+\infty} x(t) e^{-i\omega t} dt, \quad F_y(\omega) = \int_{-\infty}^{+\infty} y(t) e^{-i\omega t} dt \tag{3}$$

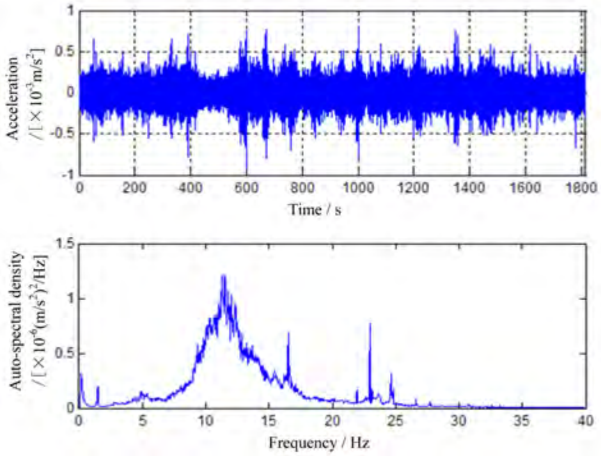


Figure 11. Time history and auto-spectrum of acceleration response at measurement point 2 in the x-direction.

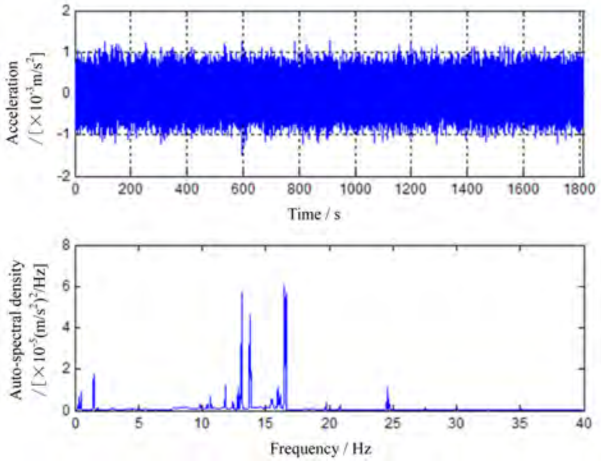


Figure 12. Time history and auto-spectrum of acceleration response at measurement point 11 in the x-direction.

The cross-spectrum of the two time histories is given by

$$S_{xy}(\omega) = \lim_{T \to \infty} \frac{1}{2T} E(F_x(-\omega, T) F_y(\omega, T)) \tag{4}$$

The coherence function of the two time histories can be expressed as

$$\gamma_{xy}^2(f) = \frac{|G_{xy}(f)|^2}{G_{xx}(f) G_{yy}(f)}, \quad 0 \le \gamma_{xy}^2(f) \le 1 \tag{5}$$

where $G_{xy}(f)$, $G_{xx}(f)$ and $G_{yy}(f)$ are one-side spectra (spectral density functions) at frequency f, and they are equal to two times the two-side spectra (spectral density functions) $S_{xy}(f)$, $S_{xx}(f)$ and $S_{yy}(f)$, respectively, in the positive frequency range.

The cross-spectrum and the coherence function of the acceleration responses measured at the foundation (point 3) and at the superstructure (point 11) are shown in Fig. 13. It can be seen that there are a few peaks at the cross-spectrum but only one peak at the coherence function. The peak magnitude of the coherence function at 1.5 Hz is more than 0.8, indicating a good correlation between the foundation and the superstructure at this frequency. At other frequencies, the correlations of the building responses between the foundation and the superstructure are weak.

The cross-spectrum and the coherence function of the accelerations measured at the point 11 (37th floor) in the x- and y- direction are shown in Fig. 14 while the same quantities for the point 3 (foundation) are displayed in Fig. 15. Since the CCTV Tower is a truly three dimensional structure with coupled mechanical mode shapes, the correlation of the acceleration responses of the structure at 37th floor in the x-and y-direction is quite strong. The correlation of the accelerations responses of the structural foundation in the x- and y-direction, however, is relatively weak compared with the 37th floor, as shown in Fig. 15. Moreover, it can be seen from Fig. 16, which exhibits the cross-spectrum and the coherence function of the accelerations from the point 11 in the y-direction and the point 3 in the x-direction, that the correlations of the building responses between the foundation and the superstructure in the horizontal plane are also very weak.

The cross-spectrum and the coherence function of the acceleration responses measured at the point 11 (37th floor) and the point 12 (48th floor) in the z-direction are shown in Fig. 17. It can be seen from the coherence function that the correlation of the acceleration responses between the two locations are strong over a wider frequency range. This indicates that the measured acceleration responses at the two locations are mainly induced by the same sources of excitation.

5.3. Natural frequencies and damping ratios

The natural frequencies and damping ratios are the important dynamic characteristics of the building. With ambient vibration measurements, they can be obtained through

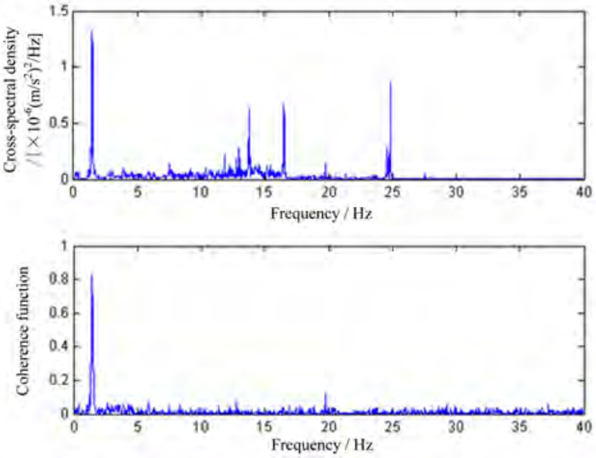


Figure 13. Cross-spectrum and coherence function of accelerations at measurement points 3 and 11 in the z-direction.

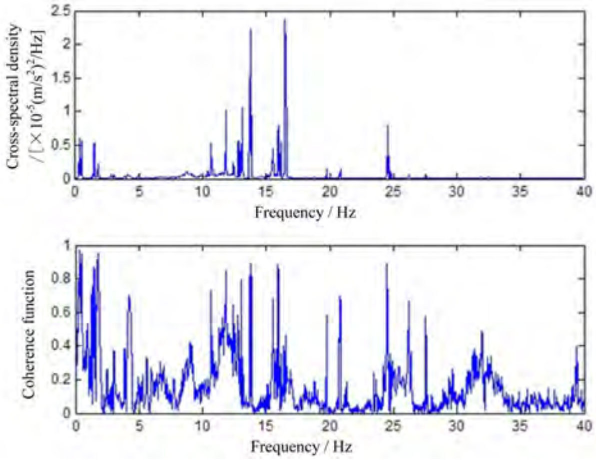


Figure 14. Cross-spectrum and coherence function of accelerations at measurement point 11 in the x- and y-directions (37th floor).

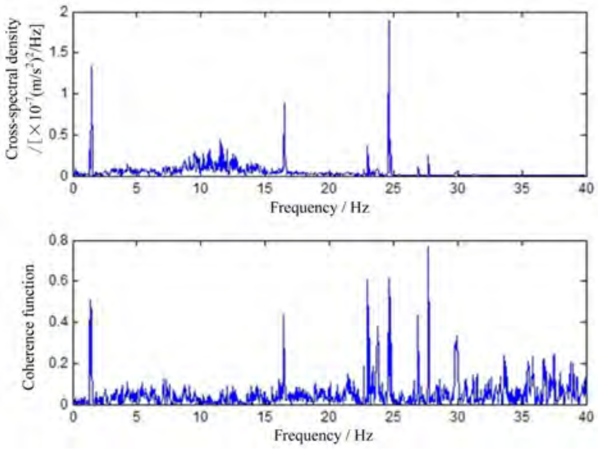


Figure 15. Cross-spectrum and coherence function of accelerations at measurement point 3 in the x- and y-directions (foundation).

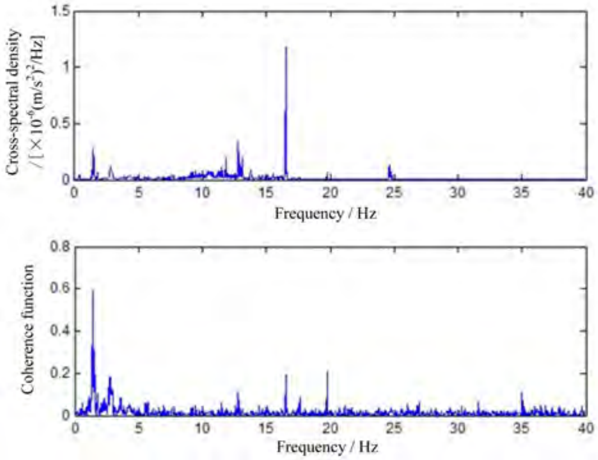


Figure 16. Cross-spectrum and coherence function of accelerations at measurement point 3 in the x-directions and point 11 in the y-direction.

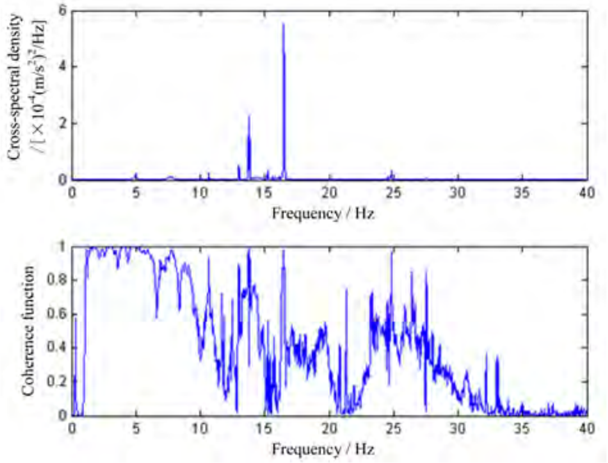


Figure 17. Cross-spectrum and coherence function of accelerations at measurement points 11 and 12 in the z-direction.

the spectral analysis of the measured acceleration response time histories by assuming the response being a stationary random process. The identified natural frequencies are quite accurate if the frequency resolution is selected fine enough. However, the identified damping ratios are not as accurate as the natural frequencies. The frequency resolution may affect the results of damping ratios significantly. To reduce the identification errors in damping ratios, the fine resolution method is used (Ying et al., 1997). The detailed procedure for the identification of damping ratio using the fine resolution method is as follows:

(1) Filter the recorded data sampled at 1000 Hz by a low pass filter with the upper frequency limit of 10 Hz. There are three data records for each channel and the duration of each record is 2 hours.

(2) Re-sample each of the above data record using a new sampling frequency $f_s = 50$ Hz, and the frequency resolution then becomes $\Delta f = 50/N$.

(3) Conduct the FFT analysis by using the DASP software with the fine resolution method (Ying et al., 1997). The frequency resolution selected is 0.00488 Hz. The software then gives the natural frequency and damping ratio corresponding to the peak in the Fourier amplitude spectrum graph (see Fig. 18).

A trade-off of the bias error and random error has to be made in the above analysis by selecting an appropriate frequency resolution and the number of data sets within the given length of measurement data (Guo et al., 2012). By trial and error, the number of data sets is finally selected as 351 and the frequency resolution is 0.0048 Hz, which leads a random error of about 2.7% and a bias error ranging from 9% (the fourth mode of vibration) to 33% (the first mode of vibration. The identified natural frequencies and damping ratios are listed in Table 1. These natural frequencies and damping ratios are the mean values obtained by averaging the results from a number of the data records, and the ratio of the standard deviation of the results from a number of the data records to their mean value is less than 0.7% for the natural frequencies and ranges from 15% to 37% for the damping ratios. Therefore, the identified natural frequencies and the damping ratios are acceptable from an engineering viewpoint.

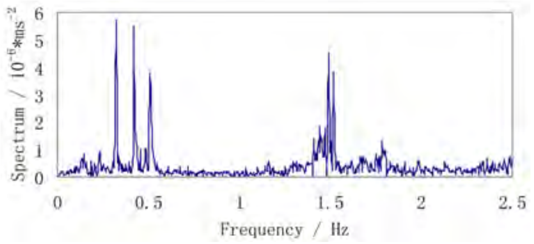


Figure 18. Spectrum with fine frequency resolution at measurement point 14 (37th floor) in the x-direction.

Table 1. Measured natural frequencies and damping ratios

Mode	Vibration	Frequency (Hz)	Damping ratio
1st	Lateral bending	0.323	0.59%
2nd	Lateral bending	0.423	0.50%
3rd	Torsional	0.511	0.55%
4th	Vertical	1.152	0.30%

5.4. Comparison of natural frequencies between measurement and computation

The numerically computed natural frequencies are compared with the measurement counterparts and listed in Table 2.

The finite element analysis results are smaller than the measurements by about 12~17%. Two main factors may contribute to the discrepancy. First, the glass curtain wall system was not included in the finite element model. The glass curtain wall in normal structures may be not important in terms of quantity. However, the present structure is enclosed by the glass curtain wall system entirely and its effect on the global stiffness cannot be ignored. Detailed studies of the glass curtain wall's effect on the structural frequencies are rare in literature. Second, the constructed concrete is generally stronger than the design value. Using the designed mechanical properties of the concrete will underestimate the strength and elasticity modulus, and thus the natural frequencies. However, the field testing data on the used concrete are not available for the present project.

It shall be pointed out that the above statement is case-

Table 2. Comparison of natural frequencies (Hz)

Mode (1)	FE analysis (2)	Measurement (3)	Difference [(2)(3)] / (3)
First lateral bending	0.278	0.323	13.9%
Second lateral bending	0.367	0.423	13.2%
First torsion	0.451	0.511	11.7%
First vertical mode	0.955	1.152	17.1%

dependent. In the reference (Guo et al., 2012) regarding the first three natural frequencies of Canton Tower, the finite element analysis results of the first two natural frequencies are larger than the measurement results by 3.3% and 2.2% but it is reversed by 10.4% for the third natural frequency.

6. Concluding Remarks

The new CCTV Tower in Beijing is a special tall building with a highly unusual shape and a very complicated structural system. The ambient vibration measurement was carried out on this building in the field to identify its dynamic characteristics and then compare the measured results with the numerical results from the finite element analysis. The difficulties and solutions have been highlighted in this paper for the field measurement and data analysis.

It was found that the time history and the auto-spectrum of the acceleration response of the building foundation were quite different from those of the building superstructure. The correlation between the vertical responses of the foundation and the superstructure was strong at one single frequency only, whereas generally weak at other frequencies. Nevertheless, the correlation between the acceleration responses of two different locations of the superstructure was strong over a wider frequency range. It was also found that the structural damping ratios of the CCTV Tower are small and the computed natural frequencies are smaller than the measured ones by about 12~17%.

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