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Output-only modal parameter identification of civil engineering structures

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Abstract. The ambient vibration measurement is a kind of output data-only dynamic testing where the traffics and winds are used as agents responsible for natural or environmental excitation. Therefore an experimental modal analysis procedure for ambient vibration testing will need to base itself on output-only data. The modal analysis involving output-only measurements presents a challenge that requires the use of special modal identification technique, which can deal with very small magnitude of ambient vibration contaminated by noise. Two complementary modal analysis methods are implemented. They are rather simple peak picking (PP) method in frequency domain and more advanced stochastic subspace identification (SSI) method in time domain. This paper presents the application of ambient vibration testing and experimental modal analysis on large civil engineering structures. A 15 storey reinforced concrete shear core building and a concrete filled steel tubular arch bridge have been chosen as two case studies. The results have shown that both techniques can identify the frequencies effectively. The stochastic subspace identification technique can detect frequencies that may possibly be missed by the peak picking method and gives a more reasonable mode shapes in most cases.

Key words: modal analysis; parameter identification; ambient vibration; spectra; stochastic subspace identification; engineering structures.

1. Introduction

Parameter identification through dynamic measurements is originally developed in more advanced mechanical and aerospace engineering disciplines (Ewins 1986, Ljung 1987, Juang 1994). There is a clear merit in trying to transfer this technology into civil engineering applications where we are dealing with problems which have a completely different scale, logistics and rationale, compared with mechanical and aerospace engineering counterparts. In the context of civil engineering discipline, the encountered structures are complex and large in size such as buildings, bridges. So, the parameter identification technique developed should be compatible and more effective to use in such large structures. Every single test on a new large object of infrastructure leads to something new, unforeseen or unknown which is worthy of reporting.

Experimental modal parameter identification of civil engineering structures means the extraction of modal parameters (frequencies, damping ratios and mode shapes) from dynamic measurements.

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These modal parameters will serve as basis or input to the finite element model updating, detecting and locating the possible damage in structures, long-term health monitoring of structures and the safety evaluation of structures against different severe circumstances like earthquakes, wind loads.

There are mainly three types of structural dynamic testing: (1) Forced vibration testing; (2) Free vibration testing; and (3) Ambient vibration testing. In the first method, the structure is excited by artificial means such as shakers or drop weights. By suddenly dropping a load on the structure, a condition of free vibration is induced. The disadvantage of artificial excitation methods is that traffic has to be shut down for a rather long period of time. This could be a serious problem for the infrastructures intensively used. In contrast, ambient vibration testing is not affected by the disturbances on the structures, because it uses the disturbances induced by traffic and wind as natural or environmental excitation. The service condition does not have to be interrupted by using this technique. It represents a real operating condition of the structure during its daily use.

Basically, the modal parameter identification is carried out based on both input and output measurement data through the frequency response functions (FRFs) in the frequency domain and impulse response functions (IRFs) in the time domain. For civil engineering structures, the dynamic responses (outputs) are the direct records of the sensors that are installed at several locations. However, the input or excitation level of the real structure in its operational condition is not easier to quantify. It is difficult to measure the input excitation forces acting on a real large structure. Although forced excitations such as heavy shakers and drop weights and correlated input-output measurements are available in some cases, testing method, structural complexity, and/or achievable data quality restrict these approaches to implement in practical applications. It is obvious that real operating conditions of complex structures may significantly differ from those of controlled laboratory environments. Due to this reason, the need to identify modal models under real operational conditions often arises.

The output-only data dynamic testing has an advantage of being inexpensive since no equipment is needed to excite the structure. The ambient vibration testing is a kind of output-only data dynamic test method. The modal parameter identification technique through ambient vibration measurements has become a very attractive topic in the area of civil engineering structures. The ambient vibration testing has been successfully applied to many large scale bridges such as the Golden Gate Bridge (Abdel-Ghaffer and Scanlan 1985), the Fatih Sultan Mehmet Suspension Bridge (Brownjohn *et al*. 1992), the Tsing Ma Suspension Bridge (Xu *et al*. 1997), the Hitsuishijima Bridge, one of the Honshu-Shikoku Bridge (Okauchi *et al*. 1997), the Vasco da Gama Cable-Stayed Bridge (Cunha *et al*. 1999), the Kap Shui Mun Cable-Stayed Bridge (Chang *et al*. 2001), the Roebling Suspension Bridge (Ren *et al*. 2001), the steel girder arch bridge (Ren *et al*. 2003), and the old masonry temples (Jaishi *et al*. 2003). In the case of ambient vibration testing, only response data are measured and actual loading conditions are unknown. A modal parameter identification procedure will therefore need to base itself on output-only data.

The modal parameter identification using output-only measurements presents a challenge that needs the use of special identification techniques, which can deal with very small magnitudes of ambient vibration contaminated by noise without the knowledge of input forces. Over the past decades, the technique of experimental modal parameter identification of civil engineering structures has developed very fast. There have been several output-only data modal parameter identification techniques available that were developed by different investigators for different uses such as: peak-picking from the power spectral densities (Bendat and Piersol 1993), auto regressive-moving average (ARMA) model based on discrete-time data (Andersen *et al*. 1996), natural excitation technique

(NExT) (James *et al*. 1995), and stochastic subspace identification (Van Overschee and Moor 1996, Peeters and De Roeck 2000). The benchmark study has been carried out to compare modal parameter identification techniques for evaluating the dynamic characteristics of a real building on operation conditions from ambient vibration data (De Roeck *et al*. 2000).

In fact, the mathematical background of output-only modal parameter identification methods is often very similar. The difference is often due to implementation aspects such as data reduction, type of equation solvers, sequence of matrix operations, etc. Consequently, the question arises to compare those analysis techniques with regard to full-scale structures. The paper is intended to compare the modal parameter identification techniques for evaluating the dynamic characteristics of a real building and a real bridge on operation conditions from ambient vibration data. Two system identification techniques used are the frequency domain-based peak picking (PP) method and the time domain-based stochastic subspace identification (SSI) method. It has not been the intention to elect a winner among the system identification techniques from ambient vibration data. The intention is to convey the fact that several of the methods can complement one another in practical application. The preferable method depends solely on the nature of actual application.

2. Output-only modal parameter identification

Ambient excitation testing does not directly lend itself to FRFs or IRFs calculations because the input forces are not measured. In the paper two modal parameter identification methods that can deal with ambient vibration measurements are implemented. The first is a rather simple peak picking (PP) method. Though it has some theoretical drawbacks, the peak-picking method is probably the most widely used method in civil engineering because of its simplicity. The second method is complementary. It is the advanced stochastic subspace identification (SSI) method, which is more time-consuming than peak picking but yields more accurate results. The theory behind the two experimental modal parameter identification techniques is briefly summarized.

2.1 Peak-picking method (PP)

The peak pick method is the simplest known method for identifying the modal parameters of civil engineering structures subjected to ambient vibration loading. The method is initially based on the fact that the FRF goes through extreme values around the natural frequencies. The frequency at which this extreme value occurs is a good estimate for the frequency of the system. In the context of ambient vibration measurements the FRF is only replaced by the auto spectra of the ambient outputs (Bendat and Piersol 1993). In such a way the natural frequencies are simply determined from the observation of the peaks on the graphs of the averaged normalized power spectral densities (ANPSDs). The ANPSDs are basically obtained by converting the measured accelerations to the frequency domain by a discrete Fourier transform (DFT).

Although the input forces are not measured in ambient vibration testing, this problem has often been circumvented by adopting a derived modal parameter identification technique where the reference sensor (base station) signal is used as an “input” and the FRFs and coherence functions are computed for each measurement point with respect to this reference sensor. It not only helps in the identification of the resonances, but also yields the operational shapes that are not the mode shapes, but almost always correspond to them. The coherence function computed for two simultaneously recorded output signals has values close to one at the resonance frequencies because of the high signal-to-noise ratio at these frequencies. Consequently inspecting the coherence function may assist to select the frequencies.

In current peak picking method, the components of the mode shapes are determined by the values of the transfer functions at the natural frequencies. Note that in the context of ambient testing, transfer function does not mean the ratio of response over input force, but rather the ratio of response measured by a roving sensor over response measured by a reference sensor. So every transfer function yields a mode shape component relative to the reference sensor. Here it is assumed that the dynamic response at resonance is only dominated by one mode. The validity of this assumption increases as the modes are better separated and as the damping in the structure is lower.

The peak picking is a kind of frequency domain based technique. Frequency domain algorithms are most popular, mainly due to their simplicity and processing speed, and also for historical reasons. These algorithms, however, involve averaging temporal information, thus discarding most of their details. Peak-picking technique has some theoretical drawbacks:

- Picking the peaks is always a subjective task;
- Operational deflection shapes are obtained instead of mode shapes;
- Only real modes or proportionally damped structures can be deduced by the method;
- Damping estimates are unreliable.

In spite of these drawbacks many civil engineering cases exist where the peak-picking technique is successfully applied. The popularity of the method is due to its implementation simplicity and its speed.

2.2 Stochastic Subspace Identification (SSI)

It is beyond the scope of this paper to explain all detail about the stochastic subspace identification method. The interested reader may refer to literatures (Van Overschee and De Moor 1996, Peeters and De Roeck 1999b). In this paper only the main issues are explained.

It is well known that a structural model can be described by a set of linear second-order differential equations with constant coefficient:

$$M\ddot{U}(t) + C\dot{U}(t) + KU(t) = F(t) \tag{1}$$

where M, C and K are the time-invariant mass, damping and stiffness matrices respectively of the structure associated with the n generalized coordinates comprising the vector $U(t)$. $F(t)$ is a time-dependent vector of input forces. Eq. (1) can be rewritten as a first-order system of differential equations in a number of ways. One commonly used reformulation in a state-space representation is:

$$\dot{x}(t) = A_c x(t) + B_c u(t) \tag{2}$$

where the state vector $x(t) = [U(t), \dot{U}(t)]^T$, the state matrix A_c and the system control influence coefficient matrix B_c are defined by

$$A_c = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix} \qquad B_c = \begin{bmatrix} 0 \\ M^{-1}B_2 \end{bmatrix} \qquad F(t) = B_2 u(t) \tag{3}$$

Furthermore, the output vector of interest, $y(t)$, can be a part of, or a linear combination of system states, such as

$$y(t) = Cx(t) + Du(t) \tag{4}$$

Here C is a real output influence coefficient matrix and D is the out control influence coefficient matrix. Eqs. (2) and (4) constitute a continuous-time state-space model of a dynamic system. Continuous-time means that the expressions can be evaluated at each time instant. Of course this is not realistic because experimental data are discrete in nature. The sample time and noise are always influencing the measurements. After sampling the continuous-time state-space model looks like

$$x_{k+1} = Ax_k + Bu_k \tag{5a}$$

$$y_k = Cx_k + Du_k \tag{5b}$$

where $x_k = x(k\Delta t)$ is the discrete time state vector; $A = \exp(A_c\Delta t)$ is the discrete state matrix; $B = [A - I]A_c^{-1}B_c$ is the discrete input matrix. Eq. (5) forms a discrete-time state-space model of a dynamic system.

In practice there are always system uncertainties including process and measurement noises. The process noise is due to disturbances and modeling inaccuracies, whereas the measurement noise is due to sensor inaccuracy. If the stochastic components (noise) are included Eq. (5) can be extended to consider process noise w_k and measurement noise v_k described as continuous-time stochastic state-space model

$$x_{k+1} = Ax_k + Bu_k + w_k \tag{6a}$$

$$y_k = Cx_k + Du_k + v_k \tag{6b}$$

It is difficult to determine accurately the individual process and measurement noise characteristics and thus some assumptions are required. Here the process noise w_k and measurement noise v_k are assumed to be of zero-mean, white and with covariance matrices:

$$E\left[\begin{pmatrix} w_p \\ v_p \end{pmatrix}(w_q^T \ \ v_q^T)\right] = \begin{pmatrix} Q & S \\ S^T & R \end{pmatrix}\delta_{pq} \tag{7}$$

where E is the expected value operator and δ_{pq} is the Kronecker delta. The sequences w_k and v_k are assumed statistically independent of each other.

In the practical problem of civil engineering structures, the reality is that only the responses of a structure are measured, while the input sequence u_k remains unmeasured. In the case of ambient vibration testing, it is impossible to distinguish the input term u_k from the noise terms w_k, v_k in Eq. (6). Modeling the input term u_k by the noise terms w_k, v_k results in a purely stochastic system:

$$x_{k+1} = Ax_k + w_k \tag{8a}$$

$$y_k = Cx_k + v_k \tag{8b}$$

The input is now implicitly modeled by the noise terms w_k, v_k. However the white noise assumptions of these noise terms cannot be omitted. The consequence is that if this white noise assumption is violated, for instance if the input contains also some dominant frequency components in addition to white noise, these frequency components cannot be separated from the eigenfrequencies of the system and they will appear as poles of the state matrix A.

Eq. (8) constitutes the basis for the time-domain system identification through ambient vibration measurements. There have been several techniques to realize system identification algorithms based on Eq. (8). The stochastic subspace identification algorithm is probably the most advanced method known up to date for ambient vibration measurement system identification. The subspace method identifies the state space matrices based on the measurements and by using robust numerical techniques such as QR-factorization, singular value decomposition (SVD) and least squares. Loosely said, the QR results in a significant data reduction, whereas the SVD is used to reject the noise (assumed to be represented by the higher singular values). Once the mathematical description of the structure (the state space model) is found, it is straightforward to determine the modal parameters (by an eigenvalue decomposition): natural frequencies, damping ratios and mode shapes.

The key concept of SSI is the projection of the row space of the future outputs into the row space of the past outputs. The main difference with the proceeding algorithms is that the subspace algorithm is data driven instead of covariance driven so that the explicit formation of the covariance matrix is avoided. It is clear that the stochastic subspace identification is a time domain method that directly works with time data, without the need to convert them to correlations or spectra. Common to all system identification methods for ambient vibration measurements, it is not possible to obtain an absolute scaling of the identified mode shapes (e.g. mass normalization) because the input remains unknown.

3. Case studies

3.1 Reinforced concrete building

The first case studied is a 15 story reinforced concrete shear core building, called the Heritage Court Tower as shown in Fig. 1, located in the downtown in Vancouver, B.C. in Canada. This building was tested on the initiation of the Dynamic Testing Group from the Department of Civil Engineering at the University of British Columbia (UBC) in the spring 1998. In plan view the building is essential rectangular in shape with only small projections and setbacks. The elevator and stairs are concentrated at the centre core of the building and form the main lateral resisting elements for wind and seismic lateral and torsional forces. The building was in the final stage of construction when it was tested.

The structure is assumed to be excited by natural ambient vibration provided by wind, traffic and human activity. The measured accelerations are taken for a long duration to ensure that all the modes of interest are sufficiently excited. Measurements are taken at predetermined locations which will capture the desired degrees of freedom of the structures. Eight horizontal accelerometers were used for the ambient vibration measurements, two of which were allocated as reference sensors (base stations) always located on the 14^{th} floor. Six accelerometers were used as roving sensors (moveable stations). Five setups were conducted to accurately capture the natural frequencies and mode shapes. Measurements were taken in two locations on every second floor beginning from the

Fig. 1 The Heritage Court Tower

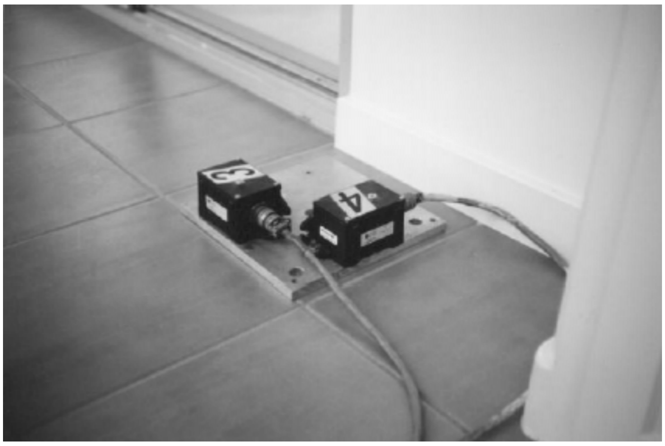


Fig. 2 Photo of accelerometers installed on the floor

roof of the uppermost penthouse down to the 2nd floor. Final measurements were taken in three locations on the ground level. Fig. 2 shows a typical accelerometer setup in the floor of the building.

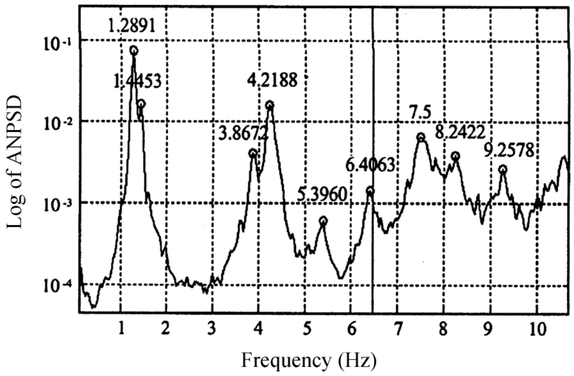


Fig. 3 Averaged normalized power spectral density (ANPSD)

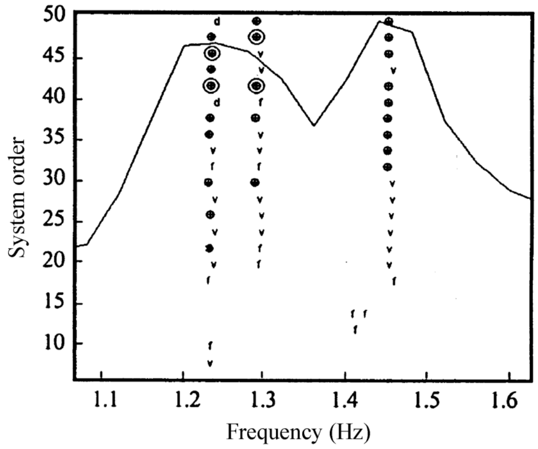


Fig. 4 Zoomed stabilization diagram of SSI (Setup1)

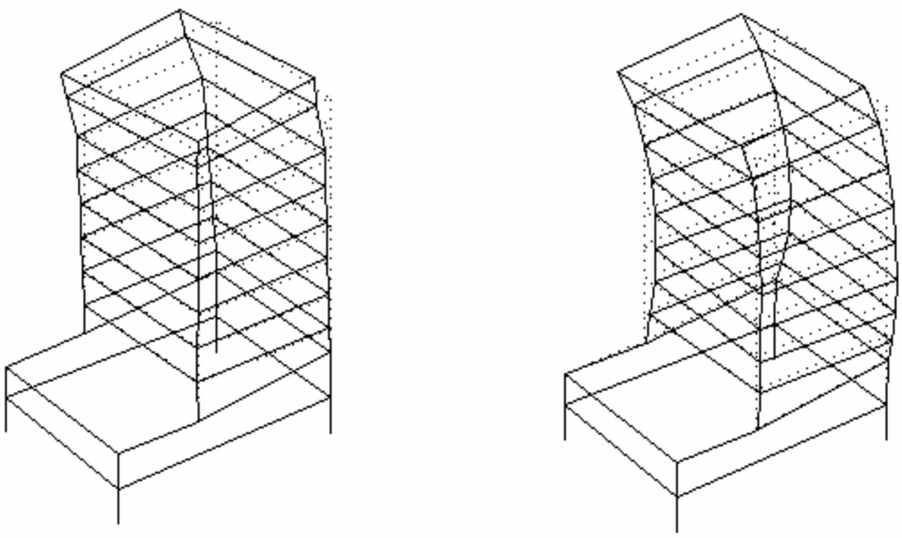
Sensors (forced-balanced accelerometers) convert the physical excitation into electrical signals. Cables are used to transmit these signals from sensors to the signal conditioner. Signal conditioner unit is used to improve the quality of the signals by removing undesired frequency contents (filtering) and amplifying the signals. The amplified and filtered analog signals are converted to digital data using an analog to digital (A/D) converter. The signals converted to digital form are stored on the hard disk of the data acquisition computer. In the ambient vibration test, the data were sampled at a rate of 200 Hz and the anti-aliasing filter had a cut-off frequency at 50 Hz. A total of 65536 samples (327.68 sec.) were acquired for each channel per setup. More details about the building and how it was measured can be found in Dyck and Ventura (1998).

The experimental modal identification was carried out using both the peak picking technique and the stochastic subspace identification method with the help of MACEC (De Roeck and Peeters). The averaged normalized power spectral densities (ANPSDs) of the peak picking technique is presented on Fig. 3, whereas Fig. 4 shows the zoomed stabilization diagram obtained by applying stochastic subspace identification corresponding to data of setup 1. It can be clearly seen that the closed frequency around 1.2 Hz identified by the stochastic subspace method is missed in the peak picking method. For almost symmetric structures the peak picking method may become problematic since the bending modes along any of the 2 principle axes and/or any of the torsion modes are likely to have closely-spaced frequencies. For beam-like structures that is the case of bridges, this seems to be less the case. The comparison of frequencies up to 10 Hz identified by two techniques is shown in Table 1.

The measurements were typically taken in the northwest and northeast corners of the building. Assuming rigid body motion of the floor slabs, the recorded motions have been translated to the equivalent motions at the four corner nodes of the model to show the full mode shapes. The two identified mode shapes by the stochastic subspace technique are shown in Fig. 5. It is demonstrated that the ambient vibration data analysis of the Heritage Court Tower was sufficient to identify 9 modes below 10 Hz. The results also show consistent coupling of the torsional and transverse modes in higher modes.

Table 1 Identified frequencies (Hz)

Mode	Stochastic Subspace		Peak Picking
	f (Hz)	ξ (%)	f (Hz)
1	1.243	1.4	NA
2	1.290	1.5	1.289
3	1.457	1.5	1.445
4	3.868	1.6	3.867
5	4.415	3.4	4.219
6	5.386	2.5	5.390
7	6.445	5.7	6.406
8	7.740	2.8	7.500
9	8.913	2.5	9.258



(a) Mode 1 at 1.243 Hz (b) Mode 3 at 1.457Hz

Fig. 5 Identified mode shapes of the Heritage Court Tower by SSI

3.2 Concrete filled steel tubular arch bridge

The second case studied is a half-through arch bridge with the span of 90 m. The bridge is named as Beichuan Bridge that lies over the Beichuan River in Xining, Qinghai Province, China as shown in Fig. 6. The specific feature of the bridge is that the arch is made by the concrete filled steel tube The ratio of rise to span of the bridge is 1/5. The axial line of the rib is the catenary and the coefficient of the axial line is 1.167. The main ribs are truss structure, which are made of 4 steel tubes, with the diameter of 650 mm. In total, 16 suspenders are used to suspend the bridge deck.

The field ambient vibration testing was carried out just prior to the official opening of the bridge on June 17-18, 2002. The objective of testing is to obtain the baseline dynamic characteristics and to calibrate the finite element model. Measurement locations were selected on the deck near the

Fig. 6 Beichuan concrete filled steel tubular arch bridge

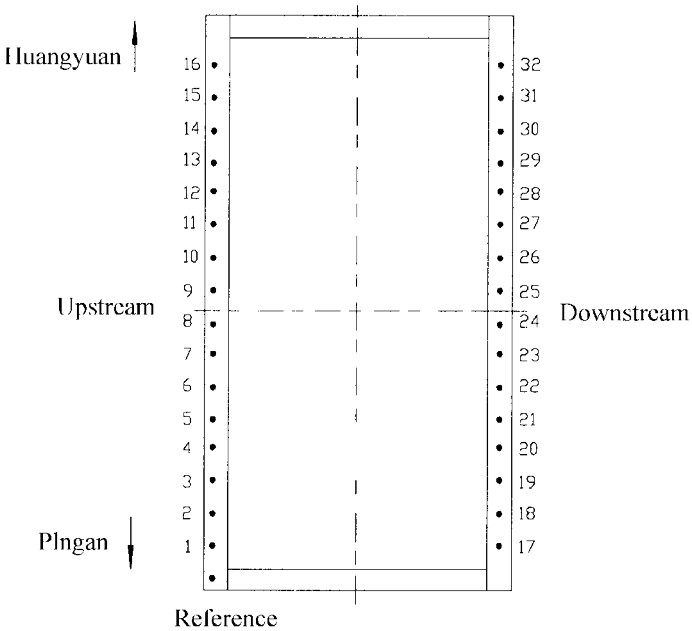


Fig. 7 Accelerometer instrumentation

location of connection between suspenders and deck. A total of 32 locations were measured. The accelerometer arrangement is shown in Fig. 7. The accelerometers were arranged in the vertical direction only. A view on the measurement instrumentations on the bridge deck is shown in Fig. 8. Four test setups were conceived to cover the planned testing area of the arch span of the bridge. Reference accelerometer (base station), located at the bearing, was common to each setup. As a result, each setup consisted of one reference accelerometer and eight moveable accelerometers. Table 2 shows the distribution of the different measured points per setup.

Fig. 8 Photo of vertical accelerometers installed on the bridge deck

Table 2 Measured points per setup

Setup	Measured points
1	1, 2, 3, 4, 5, 6, 7, 8, Reference
2	9, 10, 11, 12, 13, 14, 15, 16, Reference
3	17, 18, 19, 20, 21, 22, 23, 24, Reference
4	25, 26, 27, 28, 29, 30, 31, 32, Reference

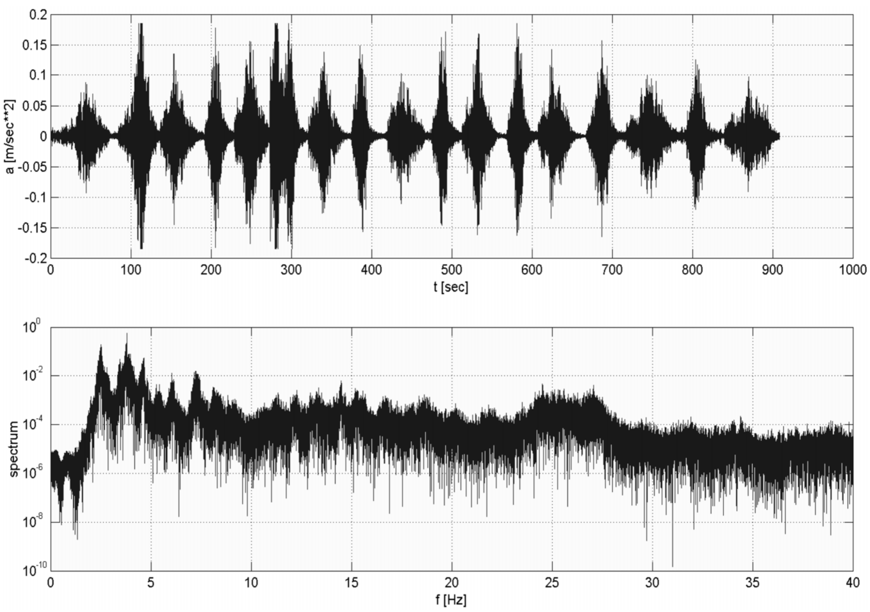


Fig. 9 Raw measurement data of Point 8

The sampling frequency on site is 80 Hz with 40 Hz cut-off frequency. The recorded time is about 15 minutes that results 72,704 data points per channel. Fig. 9 shows the raw measurement data of Point 8 visualized both in time domain and frequency domain. It is apparent that the ambient vibration records are highly stochastic and the power spectral density (PSD) contains a large range of frequencies. For most bridges, however, the frequency range of interest lies between 0 and 10 Hz, containing at least the first ten frequencies within this range. So a re-sampling of the raw measurement data is necessary.

Before identification procedure the measurement data was decimated with factor 4: it was filtered through a digital low-pass filter with a cut-off frequency of 10 Hz and resampled at 20 Hz. This operation reduces the number of data points and makes the identification more accurate in the considered frequency range 0~10 Hz. The decimating 4 times of raw data results in 72,704/4=18,176 data points per channel. Even after re-sampling, the power spectral density in the frequency domain is still not so good. A much smoother spectrum can be obtained by adjusting the PSD parameters. A window length of 1024 data points is then selected. Subsequently, the PSD is taken for all succeeding blocks of 1024 data points and an excellent noise-free PSD is obtained. The re-sampling measurement data visualized in the time domain and the modified PSD visualized in the frequency of Point 8 are shown in Fig. 10. The data is now ready for the modal identification procedure to extract the modal parameters.

The identified frequencies by the two complementary methods are listed in Table 3. As usual, the modal parameters are selected from a stabilization diagram. It can be found that a good agreement of identified frequencies by the peak picking and stochastic subspace identification methods. The first three vertical bending mode shapes identified by the stochastic subspace identification are

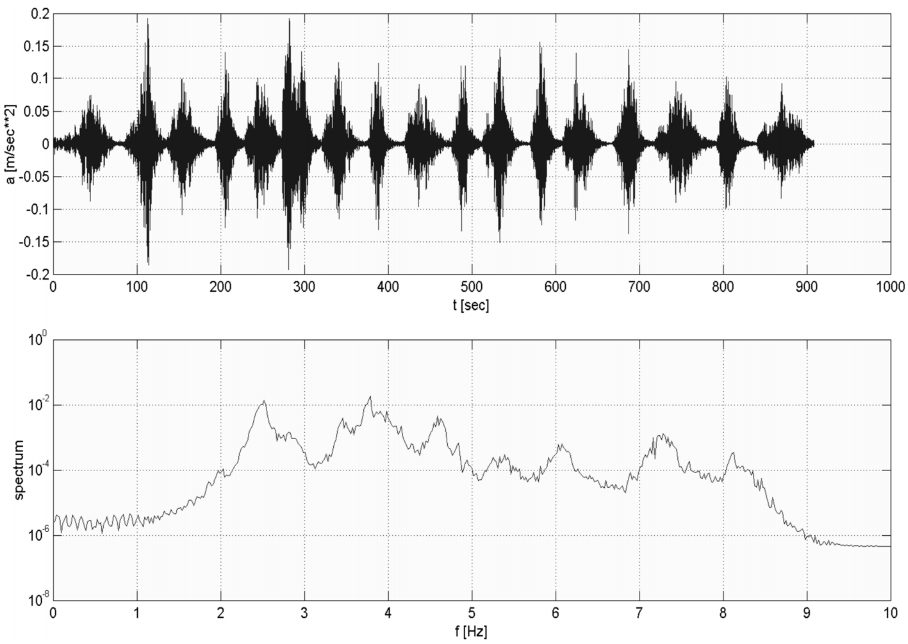
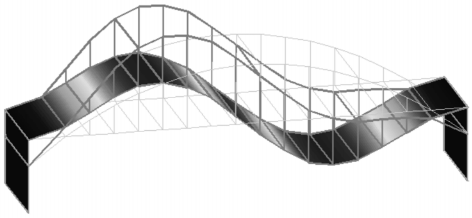
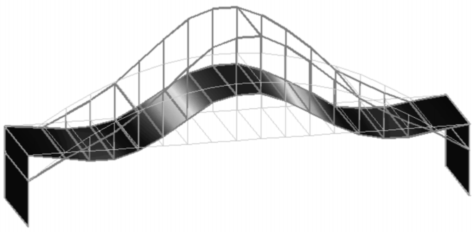


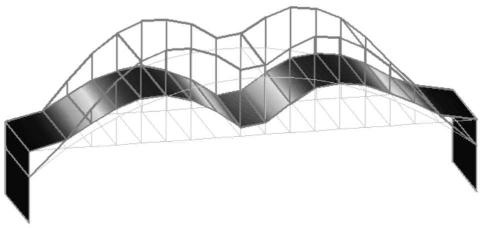
Fig. 10 Re-sampled data and modified power spectral density of Point 8



(10) 1st Vertical Mode Shape (f=2.002Hz, ξ=0.8%)



(b) 2nd Vertical Mode Shape (f=2.511Hz, ξ=2.4%)



(c) 3rd Vertical Mode Shape (f=2.827Hz, ξ=1.0%)

Fig. 11 Identified mode shapes of the Beichuan arch bridge

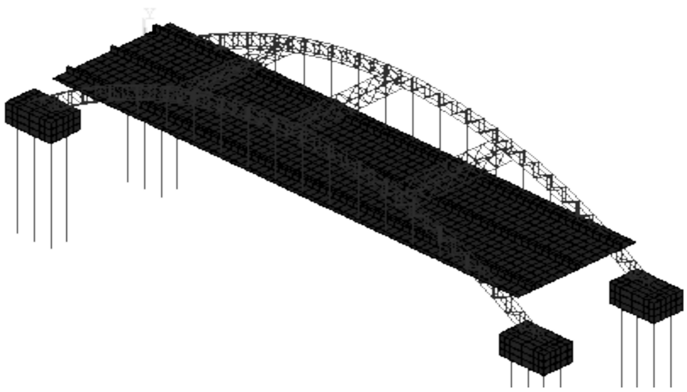


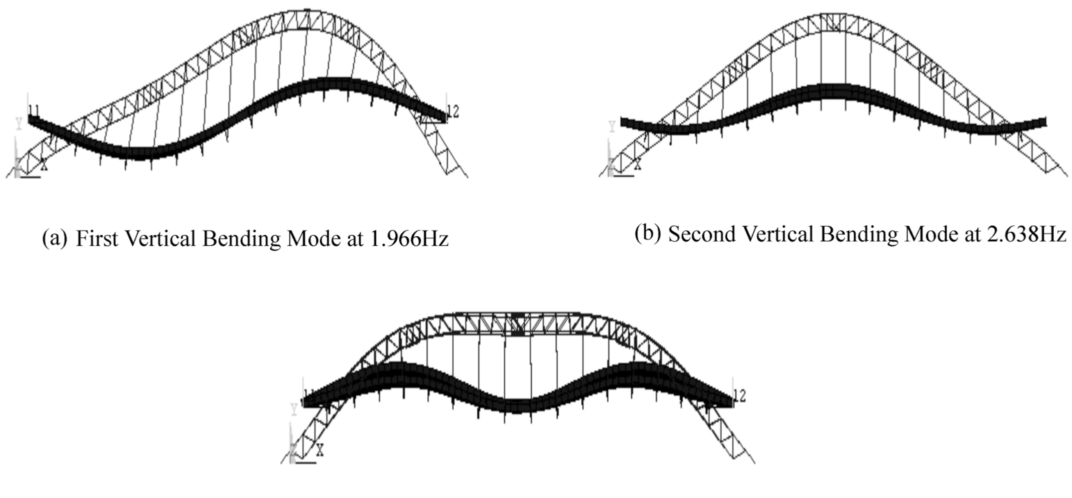
Fig. 12 Three-dimensional finite element model of Beichuan arch bridge

shown in Fig. 11. It is demonstrated that the stochastic subspace identification provides excellent mode shapes. The resolution of higher modes is not good as that for the lower modes due to the limited number of measurement location. The results show that the ambient vibration measurements of the Beichuan arch bridge are sufficient to identify 8 modes below 10 Hz.

The three-dimensional finite element (FE) model of the Beichuan arch bridge, as shown in Fig. 12, was established in the environment of ANSYS, a popular FE software. The analytical modal analysis results were complemented with those obtained from field ambient vibration testing. The calculated frequencies are compared in Table 3. The calculated first three vertical bending mode shapes are shown in Fig. 13. It is demonstrated that a good agreement is achieved between the field ambient vibration test and FE calculation. The FE model that is validated can serve as the baseline FE model for the future use.

Table 3 Identified and calculated frequencies

Mode	Finite element calculation (Hz)	Peak-picking (Hz)	Stochastic subspace identification	
			Frequency (Hz)	Damping ratio (%)
1st vertical	1.966	2.012	2.002	0.8
2nd vertical	2.638	2.519	2.511	2.4
3rd vertical	2.784	2.812	2.827	1
4th vertical	3.501	3.457	3.473	1.2
5th vertical	4.106	3.926	3.864	1.9
6th vertical	4.512	4.628	4.624	1.3
7th vertical	6.107	5.390	5.419	1.5
8th vertical	6.665	6.074	6.053	1.1



(a) First Vertical Bending Mode at 1.966Hz

(b) Second Vertical Bending Mode at 2.638Hz

(c) Third Vertical Bending Mode at 2.784Hz

Fig. 13 Calculated vertical bending mode shapes of the Beichuan arch bridge

4. Conclusions

In this paper the output-only modal parameter identification of full-size large civil engineering structures has been presented. Using two independent numerical techniques, noise was filtered and most important frequencies/mode shapes were identified. It has been shown how the modal parameters are extracted from ambient vibration measurements by using the peak-picking (PP) method and the stochastic subspace identification (SSI) technique. A good agreement of identified frequencies has been found between two methods. However, it is recognized that the stochastic subspace identification method provides a better mode shape than the peak picking method.

In the peak-picking method the natural frequencies are selected as the peaks of the ANPSDs. This becomes a quite subjective task, especially if the peaks are not very clear. But in the case of SSI method stabilization diagrams aid the engineer to select the true modes. One of the advantages of the SSI method is that the stabilization diagram can be constructed in an effective way. The computationally more time-consuming steps (QR and SVD) have to be performed only once. Afterwards models of increasing order are obtained by rejecting less singular values.

In the PP method, since no modal model is fitted to the data, operational deflection shapes are obtained instead of mode shapes. If the modes are well separated, this is no major drawback, because an operational deflection shapes is very similar to a mode shape. Even though PP has this weak point, the method is strong and useful since the identification is very fast. The SSI technique is probably the most advanced method known up to date for modal parameter identification using field ambient vibration measurements. Based on stabilization diagram, this technique can detect frequencies that may possibly be missed by the PP method. The computational load of the SSI technique is significantly higher than the PP method and the quality of the identification is also higher.

The modal parameter identification of real civil engineering structures using field ambient vibration measurements is a complicated procedure. It is essential to verify the identified results by using other independent identification techniques. The application of supplementary techniques will increase the reliability of identified results. For civil engineering structures, it is suggested that the peak picking technique could be used on site to make a quality check of the acquired data and to judge the overall dynamic characteristics of the structure. And then, back at the office, the stochastic subspace identification technique could be applied to carryout detail analysis or to ensure the results.

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