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Dynamic field monitoring data analysis of an ancient wooden building in seismic and operational environments

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Abstract. The engineering background of this article is an ancient wooden building with extremely high historic and cultural values in Tibet. A full understanding of the dynamic behaviour of this historic building under in-service environments is the basis to assess the condition of the structure, especially its responses to earthquake, environmental and operational loading. A dynamic monitoring system has been installed in the building for over one year and the large amounts of high quality data have been obtained. The paper aims at studying the dynamic behaviour of the wooden building in seismic and operational conditions using the field monitoring data. Specifically the effects of earthquake and crowd loading on the structure's dynamic response are investigated. The monitoring data are decomposed into principal components using the Singular Spectrum Analysis (SSA) technique. The relationship between the average acceleration amplitude and frequencies of the principle components and operational conditions has been discussed. One main contribution is to understand the health condition of complex ancient building based on large databases collected on the field.

Keywords: dynamic monitoring system; historic building; seismic and operational environments; data analysis

1. Introduction

Heritage structures are historical constructions that have an important role in the cultural heritage of society. Nevertheless, degradation processes generated by natural or human actions lead to deterioration, damaging or even loss of these inestimable treasures. Dynamic response of structures is strongly influenced by the conservation state of materials and structural lesions. Structural Health Monitoring (SHM) techniques make it possible to detect the presence of lesions and estimate the severity of the structural damage by monitoring vibration of the buildings. In recent years, dynamic monitoring systems have been installed in several ancient buildings to investigate the behavior of those structures (Glisic *et al*. 2007, Quaranta *et al*. 2012, Calcina *et al*.

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2013, Gentile *et al.* 2014). To develop rigorous and reliable approaches for assessing the condition of ancient structures, the dynamic response of the building in its varying environmental and operational conditions must be ascertained.

Many methods for the extraction of modal parameters from dynamic measurements have been developed and the effect of environmental and operational loads on modal parameters of bridge structures has been investigated (Ivanovic *et al.* 2000). Earthquake Data recorded have enabled preliminary studies of the space-time variation of earthquake ground motions and their effects on the structure (Loh *et al.* 1982, Harichandran and Vanmarcke 1986). The dynamic responses of structures are markedly different during strong ground motion with that under small amplitude ambient conditions. The effect of operational and environmental conditions on dynamic parameters of the structure has been studied and some features are very sensitive to earthquake, environmental and operational conditions. Strong ground motion duration is an important parameter for seismic risk assessment which greatly affects the amount of damage that will occur (Bommer and Martinez-Pereira 1999). Besides, the effect of environmental conditions on modal properties was studied. Rohrmann *et al.* (2000) observed that the variation of features of a 7-span high way bridge caused by the temperature change may reach 10% from the three years continuous monitoring data. The first three natural frequencies of the Z24 Highway Bridge were found to vary from 14% to 18% based on one year monitoring results (Peeters and De Roeck 2001). Ni *et al.* (2005) observed that normal environmental change accounts for variation in the first 10 modal frequencies from 0.20% to 1.52% based on one year monitoring of a 1177 m long cable stayed bridge. Liu and De Wolf (2007) refer that three identified frequencies of a 3-span curved highway bridge suffered changes of 5-6% induced by temperature during one full year. Zhu *et al.* (2009) studied the effect of the load carried by structures on the assessment result of the crack damage. Law *et al.* (2013) proposed a statistical indicator based wavelet packet component energy to describe the damage extent of the structure. The power spectral density transmissibility was adopted to detect the structural damage from response measurements only (Li *et al.* 2015). However, little attention has been paid to the sensitivity of modal properties of in-service ancient buildings to earthquake, environmental and pedestrian factors.

The engineering background of this article is an ancient wooden building with extremely high historical and cultural values in Tibet. The initial purpose is to check the structural response in its seismic and operational environment conditions, in order to respect appropriate vibration service ability limits (HIVOSS 2008, SÉTRA/AFGC 2006). A continuous dynamic monitoring system, required by the ancient building owner, was installed to monitor the vibration of the building. The traditional experimental procedures for dynamic identification (Gentile *et al.* 2007, Michel *et al.* 2008, Rainieri *et al.* 2010), in which a measurable input such as hammer or a shaker is applied to the system and the induced response is later interpreted (input-output identification), are neither feasible nor practical for heritage structures (Cimellaro *et al.* 2012). For this reason, output-only identification methods based on freely available ambient vibrations are becoming preferred. Acceleration data was collected at two points in a walking corridor along the tourist route inside the historic Tibetan building. This system was subsequently further developed by signal processing and output-only modal identification routines.

Expressly, the effects of seismic and operational environment conditions on the dynamic response of the structure are investigated, and their influence on the modal frequencies of the building, will modify the main features extracted from measured dynamic responses. Considerable efforts have been made to investigate environmental effects on modal properties. Vibration levels are an indirect measure of traffic intensity, may be an important operational variable affecting the dynamic properties of in-service structures which was documented for instance by Kim *et al.* (2003) that the heavy traffic may account for the 5.4% decrease of natural frequencies of a 46 m simply supported plate girder bridge, because of the added traffic mass loading. Still, this aspect has been less investigated in ancient structure, where most of vibration levels are induced by pedestrians. As well as, the effects of earthquake on modal properties was studied on this research.

Based on above information, this paper aims at ascertaining the response of the ancient building to changes in its earthquake, environmental and operational conditions, based on Singular Spectrum Analysis (SSA) which can decompose the measured response of the structure and the computed response vectors into the corresponding decomposition subspace to remove the effect of measurement noise (Liu *et al.* 2013). The possible applications of SSA are diverse from mathematics (Moskvina and Zhigljavsky 2003) and physics (Marrelli *et al.* 2003) to economics (Hassani and Thomakos 2010) and finance (Hassani 2010), from meteorology (Fraedrich 1986) and oceanology (Lall *et al.* 1996) to social science (Hassani and Zhigljavsky 2009). Based on this technique, the initial response time series of the ancient building can be decomposed into meaningful components and the first three natural frequency series components both in time and frequency domain using one hour signals are used to learn the effects of seismic and operational environment on modal properties using the large amount of high quality data continuously collected by the dynamic monitoring system of an ancient wooden building last for one year. To the knowledge of the authors, the effect of earthquake, temperature and crowd loading on the ancient building's dynamic response has not been fully studied. In this study, a structure health monitoring system for the historic building is addressed and this monitoring system had provided high quality data continuously with the earthquake and environmental factors affecting them.

The layout of this paper is as follows. A brief introduction of the procedure to obtain the measured acceleration is given in next Section. Section 3 discusses on the SSA method and its application on data processing, the effects of earthquake, environmental and operational on modal properties after vibration signal component decomposition by the SSA method are also presented in this section. Finally, a summary of the study and some concluding remarks are given.

2. Dynamic monitoring of the ancient building

2.1 Description of the monitoring system

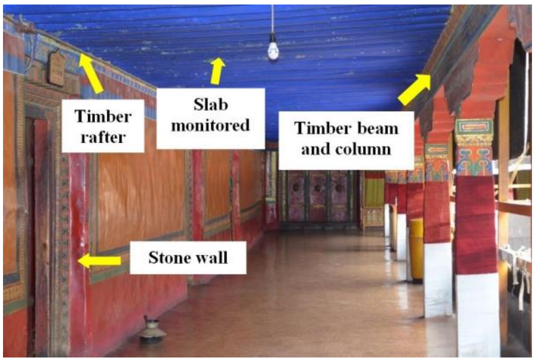


Fig. 1 Components of the structure

The ancient building is located on the mountain of Tibet, a city in the Southwest of China. The supporting slab, as shown in Fig. 1, is a typical component of Tibetan buildings that composes of the cementious material layer, waterproof layer and Agatu. The slab is supported by wooden rafters at close spacing at the bottom and framed by a wooden edge beam at one end and simply supported by stone wall at the other. The spacing and span of the rafters are roughly at 150 mm and 3500 mm respectively, as shown in Fig. 1. The slab is subjected to earthquake and dynamic loads particular from the large number of tourists visiting the building every day. The dynamic behaviour of this kind of wooden structures is also much sensitive to thermal loading (Holzer *et al.*1989).

A monitoring system has been installed in the ancient building since 2012. Acceleration data was collected at two points in a walking corridor along the tourist route inside the historic Tibetan building, as shown in Fig. 2. The accelerometers were placed in the tourist-intensive areas to record the dynamic response of the supporting floor. The grey area in Fig. 2 denotes the exhibition halls, and the path of tourists along the corridor is marked by arrows. Sensor #1 is close to the building entrance, and Sensors #2 is further down the tourist route. The location of Sensor #1 relative to the corridor is depicted in Fig. 3(a). The sensor was placed in the middle of corridor fenced off along the middle of the space for two-way pedestrian movement. Sensor #2 was in front of the door of an exhibition hall, as shown in Fig. 3(b). The accelerometers are of model KD1300C from Yang Zhou Ke Dong. The data acquisition system is of model INV3060A from the China Orient Institute of Noise and Vibration with 16 channels which can be seen in Fig. 3(c). The measuring duration lasts for one hour each day from 10 am to 11 am. The sampling frequency is selected at 512 Hz.

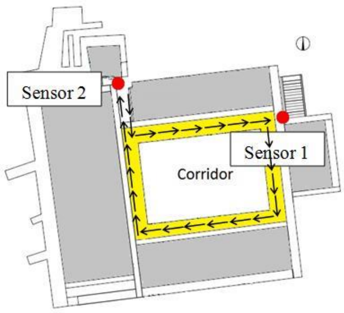
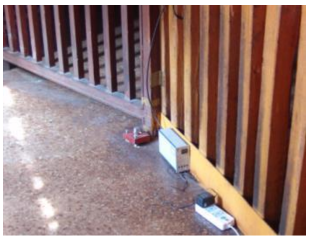


Fig. 2 The map of the historic building



(a) Location map of Sensor #1

(b) Location map of Sensor #2

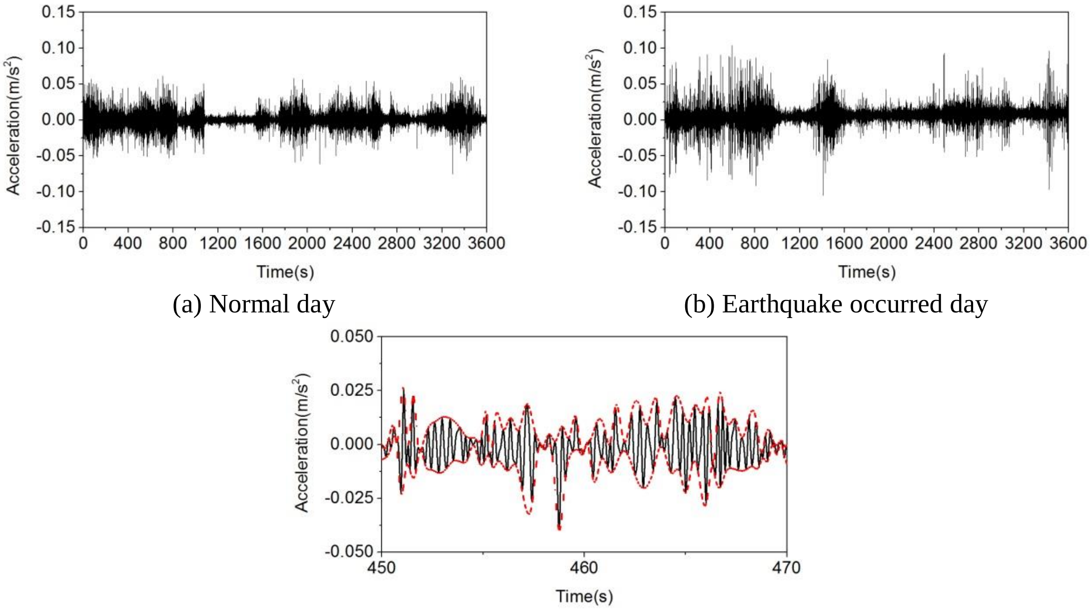
(c) Data acquisition system and acquisition software

Fig. 3 Dynamic monitoring system

Over one year of reliable monitoring data is now available from the ancient building monitoring system, which provides a most unique opportunity for development of a reliable evaluation approach. Nine large earthquakes occurred during the one year monitoring, whose magnitudes were greater than level 4, and date are 5 Jan 2013, 16 April 2013, 3 June 2013, 12 Aug 2013, 9 Sep 2013, 16 Sep 2013, 22 Sep 2013 and 3 Nov 2013 respectively. Although earthquakes may not occur in the measurement time, the structure's condition could be evaluated based on the difference of dynamic measurements before and after the earthquake using finite element model updating techniques. Before dynamic responses could be used to assess the condition of the building, it is very important to understand fully the variation of modal parameters in the seismic and operational environment. This study analyses the dynamic behaviour of the ancient building using the one year monitoring data.

2.2 Averaged acceleration amplitudes

Historic buildings require low vibration levels to prevent negative effects on the building use. Several international standards define vibration criteria for these types of buildings. Human-induced vibrations are usually analysed as a serviceability problem because human-beings are very sensitive to vibrations (Zivanovic *et al.* 2005). In this historic building, the vibration level plays a very important role and the averaged acceleration value is regarded as a serviceability index. Figs. 4(a) and 4(b) show typical signals from one acceleration sensor in the normal day and the earthquake occurred day, respectively. The vibration level of the slab was evaluated based on averaged absolute envelope values of acceleration measurements, as shown in Fig. 4(c). In this study, in order to detect possible excessive vibration levels induced by pedestrians, the average acceleration amplitudes were evaluated automatically from each one hour measurement.



(a) Normal day

(b) Earthquake occurred day

(c) Part of signal and its envelope

Fig. 4 A typical acceleration response in one hour

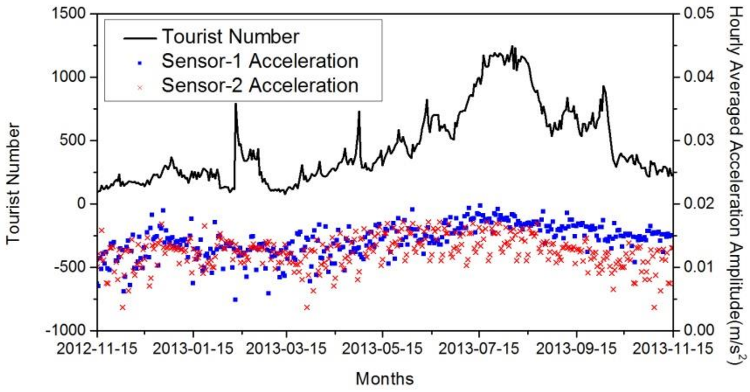


Fig. 5 Tourist number and hourly averaged acceleration amplitudes

The dynamic response measurements at Sensors #1 and #2 are used to calculate the average acceleration amplitudes. Fig. 5 shows the average daily accelerations amplitude over one year (November 15, 2012 to November 14, 2013). The figure shows the acceleration amplitude level increases with the number of tourists walking in the ancient building naturally. From Fig. 5, the effect of earthquake loading on the structural response is hard to see in time domain because earthquakes did not always occurred during the dynamic measurement. The two averaged acceleration amplitudes continuous changed during the whole year and it is hard to say whether the shift was caused by earthquake directly.

2.3 Variation of natural frequencies

In order to better understand the dynamic behavior of this structure, the frequency content of acceleration signals was analyzed. A typical power spectral density diagram of a one hour response signal is shown in Fig. 6. The power spectral densities (PSDs) of accelerations were estimated using a Hanning window with 2048 points and 50% overlap. Three natural frequencies between 10 Hz and 35 Hz were successfully identified. These natural frequencies are corresponding to the first three principal components. Based on continuous monitoring data from November 15 2012 to November 14 2013, the identified natural frequencies are shown in Fig. 7. From the figure, there are no obvious changes in these natural frequencies during this period. The results show that there are no big changes in the structure and the operation conditions, such as the crowd, temperature and earthquake loading.

3. Analysis of field monitoring data

One of the main obstacles of vibration-based SHM for practical applications is the difficulty to distinguish changes of the modal parameters due to the damage from that of the variation of operational environments. The singular spectrum analysis (SSA) decomposes a time series into a group of simple and independent components, and these components represent important characteristics of the time series, i.e., the trend, oscillating components and the uninformative

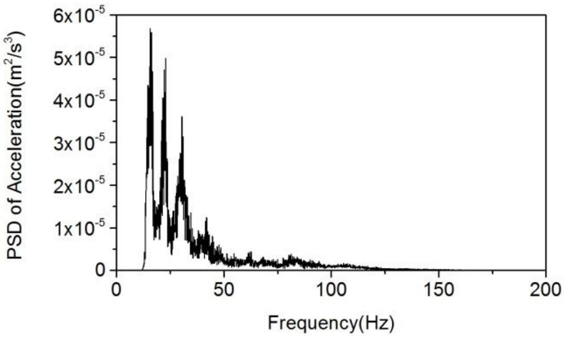


Fig. 6 A typical power spectral densities of acceleration using one hour signals

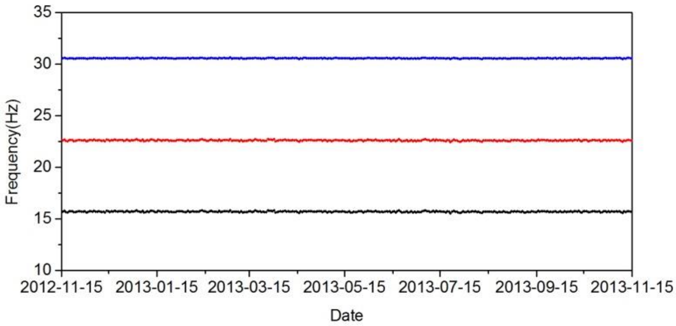


Fig. 7 Identified first three natural frequencies during one year

noise. The first several principal components contain the fundamental information of the dynamic measurements. In this study, the SSA method is adopted to decompose the time series into principal components and then the relationship between the principal component and the operational environment is analysed, especially the variation of modal parameters due to the earthquake, temperature and operational loading. The first three principal components are selected in this analysis.

3.1 Data processing using singular spectrum analysis

Before the SSA method is used for analysis, the SSA algorithm for extracting the principal components and their subsequent forecasting is introduced briefly. More details can be found in other works (Golyandina *et al.* 2001, Hassani 2007). The SSA technique consists of two complementary stages: decomposition and reconstruction, and each of them also include two separate steps. The time series is decomposed in the first stage and the selected components are used to reconstruct the signal at the second stage.

Stage 1: Decomposition

First step: Embedding

In the embedding step, a window length L is chosen firstly, where $2<L<N/2$, to embed the initial time series. Embedding can be regarded as a mapping that transfers a one-dimensional time series $Y_N=(y_0,..., y_{N-1})$ into a Hankel matrix as shown in Eq. (1). This trajectory matrix consists of

multi-dimensional series $X_1,...,X_K$ with dimensions $L\times K$ and with vectors $X_i \in R^L$, where $K=N-L+1$, and N is the length of data.

$$\mathbf{X}=\left(x_{ij}\right)_{i,j=1}^{L,K}=\begin{bmatrix} y_0 & y_1 & y_2 & \cdots & y_{K-1} \\ y_1 & y_2 & y_3 & \cdots & y_K \\ y_2 & y_3 & y_4 & \cdots & y_{K+1} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ y_{L-1} & y_L & y_{L+1} & \cdots & y_{N-1} \end{bmatrix}=[X_1 X_2 \cdots X_K] \tag{1}$$

and

$$X_i=\left(y_i\text{-}1, y_i, \ldots, y_{i+L-2}\right)^T \qquad (1 \leq i \leq K) \tag{2}$$

Second step: Singular value decomposition

The SSA is based on singular value decomposition (SVD). If we define $X_i=\sqrt{\lambda_i}\mathrm{U}_i\mathrm{V}_i^T$ (i=1,...,d), then the SVD of the trajectory matrix in Eq. (1) can be written as the sum of rank-one orthogonal matrices

$$\mathrm{X}=\mathrm{X}_1+\mathrm{X}_2+\cdots+\mathrm{X}_d=\sum_{i=1}^{d}\mathbf{X}_i=\sum_{i=1}^{d}\sqrt{\lambda_i}\,\mathrm{U}_i\mathrm{V}_i^T \tag{3}$$

where U_i and V_i stand for the left and right eigenvectors of the trajectory matrix. The collection (λ_i, U_i, V_i) is called the ith eigentriple of the matrix $\mathbf{X}$, and $\sqrt{\lambda_i}$ (i=1,..., d) are the singular values of matrix $\mathbf{X}$.

Note that $\|\mathrm{X}\|^2=\sum_{i=1}^{d}\sqrt{\lambda_i}$ and $\|\mathbf{X}_i\|^2=\lambda_i$ for i=1,…,d. Thus the ratio $\lambda_i/\sum_{i=1}^{d}\lambda_i$ can be considered as the contribution of the matrix $\mathbf{X}_i$ in the expansion in Eq. (3) to the whole trajectory matrix $\mathbf{X}$. Consequently, $\sum_{i=1}^{r}\lambda_i/\sum_{i=1}^{d}\lambda_i$, the sum of the first r ratios, is the contribution of the optimal approximation of the trajectory matrix with rank r by the matrices $\mathbf{X}_i$.

Stage 2: Reconstruction

First step: Grouping

The grouping step corresponds to splitting the elementary matrices $\mathbf{X}_i$ into several groups and summing the matrices within each group into a new series of length N. Let $I=\{i_1,\ldots,i_k\}$ be a group of indices. Then the group I corresponding to matrix $\mathbf{X}_I$ is defined as $\mathbf{X}_I=\mathbf{X}_{i1}+\ldots+\mathbf{X}_{ik}$. These matrices are computed for $I=I_1,\ldots,I_m$ groups and Eq. (3) leads to the decomposition

$$\mathbf{X}_I=\mathbf{X}_{I1}+\mathbf{X}_{I2}+\cdots+\mathbf{X}_{Im} \tag{4}$$

The procedure for choosing the sets $I_1,...,I_m$ is called eigentriple grouping.

Second step: Diagonal averaging

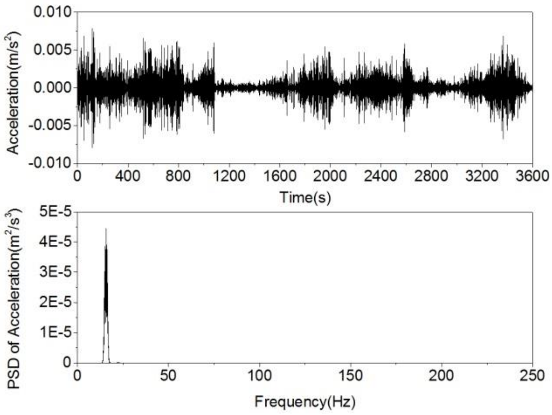
The purpose of diagonal averaging is to transform a matrix to a Hankel matrix which can subsequently be converted to a time series. If x_{ij} stands for an element of a matrix $\mathbf{X}$, then the kth term of the resulting series is obtained by averaging x_{ij} over all i and j such that $i+j=k+1$. In what follows, we use two groups of indices, $I_1=\{1,\ldots,r\}$, and $I_2=(r+1,\ldots L)$ and associate the group $I=I_1$ with the signal component and the group I_2 with noise in the original signal.

$\mathbf{X}_\mathrm{I}$ is an $L\times K$ matrix with elements x_{ij}, ($1\leq i\leq L$) and ($1\leq j\leq K$). We set $L^*=\min(L,K)$, $K^*=\max(L,K)$. Let $x_{ij}^*=x_{ij}$ if $L<K$ and $x_{ij}^*=x_{ji}$ otherwise.

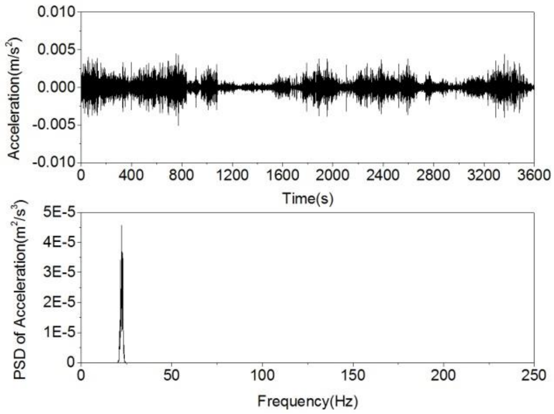
Diagonal averaging transfers the matrix $\mathbf{X}_I$ to the series $\tilde{y}_0, \tilde{y}_1, \ldots, \tilde{y}_{N-1}$ by the following formula:

$$\tilde{y}_k = \begin{cases} \frac{1}{k+1} \sum_{m=1}^{k+1} x^*_{m,k-m+2} & \text{for } \left(0 \le k < L^* - 1\right) \\ \frac{1}{L^*} \sum_{m=1}^{L^*} x^*_{m,k-m+2} & \text{for } \left(L^* - 1 \le k < K^*\right) \\ \frac{1}{N-k} \sum_{m=k-K^*+2}^{N-K^*+1} x^*_{m,k-m+2} & \text{for } \left(K^* \le k < N\right) \end{cases} \tag{5}$$

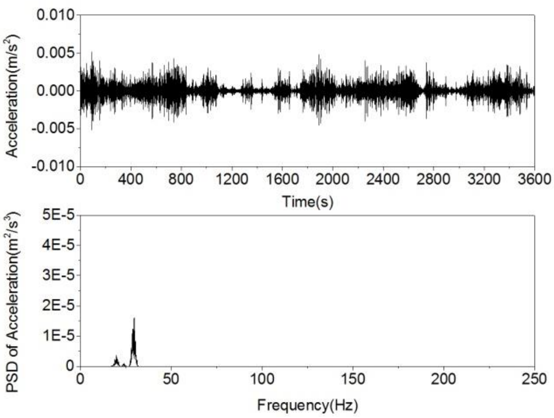
The first few significant components are usually selected to approximate the original sequence and they are reconstructed for further analysis of the original signal. It is advisable to take the window length proportional to the periods of components in the time series to achieve a better separability of these periodic components. In this study, a window length L=50 is therefore chosen based on the eigenvalue spectra and discussions on separability by Hassani and Heravi (2009). This selection covers all known periodicities and, probably, seasonal cycle components. The objective of analysis is to decompose the initial time series into meaningful components, i.e., a long-term trend, periodic components of seasonal nature, and uninformative noise.



(a) the 1st series



(b) the 2nd series



(c) the 3rd series

Fig. 8 The first three natural frequency series both in time and frequency domain using one hour signals

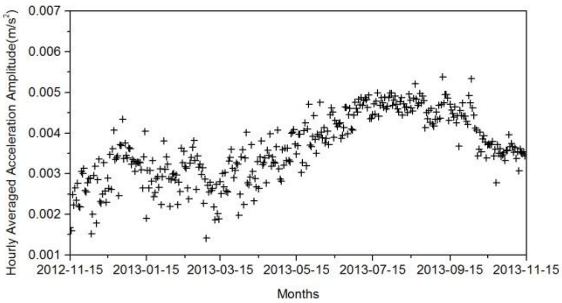
Table 1 Identified first three natural frequencies by different method

Natural frequency	PSD	SSA	SSI
The first	15.72	15.72	15.72
The second	22.58	22.60	22.58
The third	30.56	30.57	30.57

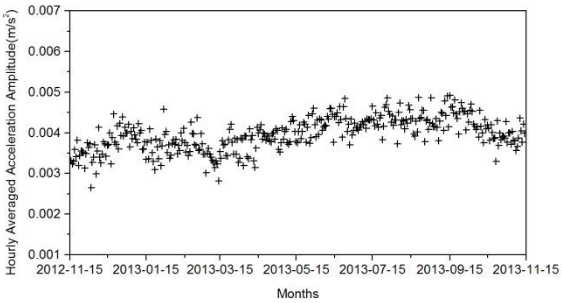
The SSA technique was applied to dynamic measurements at Sensor #1 for illustration and the first three natural frequency components in time and frequency domains can be shown in Fig. 8. To certify the accuracy of the results of modal analysis, three methods, PSD, SSA and SSI, are adopted in this study with the same typical signal in a normal day and the results are listed in Table 1. From Table 1, the results by those three methods are agreed well.

3.2 Effects of pedestrian on averaged acceleration amplitudes and natural frequencies

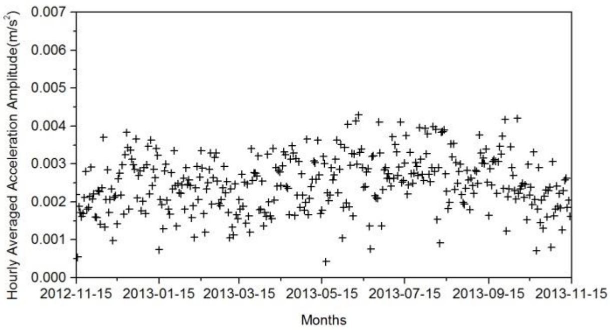
The average daily acceleration amplitude is decomposed into three time series using SSA, as shown in Fig. 9. The correlation coefficients between three components of the average daily acceleration amplitude and the tourist number are 0.81, 0.66 and 0.38 respectively. The correlation coefficient between the first component and the tourist number is higher than that of original average daily accelerations amplitude (which is 0.68). Based on long-term monitoring data, Fig. 10 plots of the average daily accelerations in the first three reconstructed series in time domain



(a) The first component

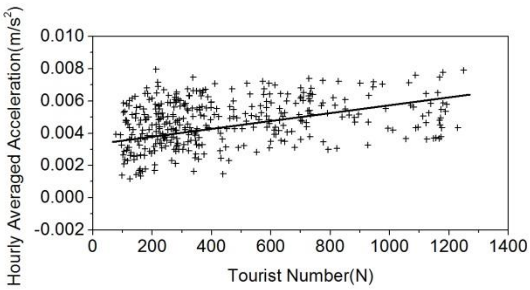


(b) The second component

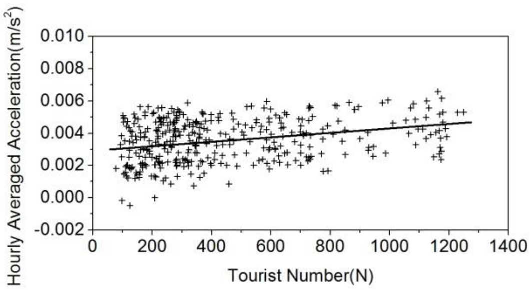


(c) The third component

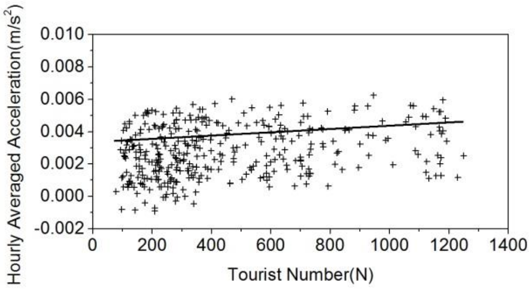
Fig. 9 Hourly averaged acceleration amplitudes time history curve



(a) the 1st series

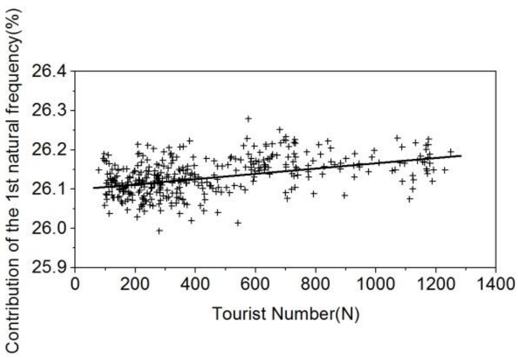


(b) the 2nd series

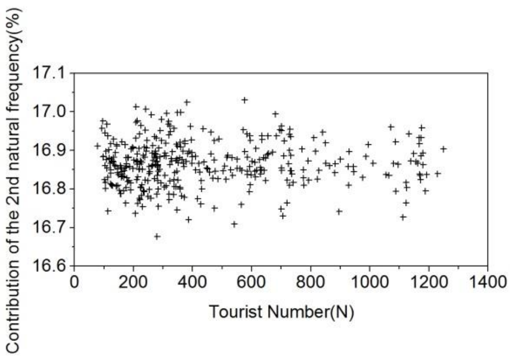


(c) the 3rd series

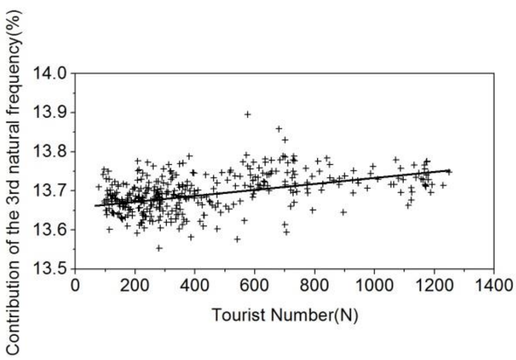
Fig. 10 Hourly averaged acceleration amplitudes vs tourist number



(a) the 1st series



(b) the 2nd series



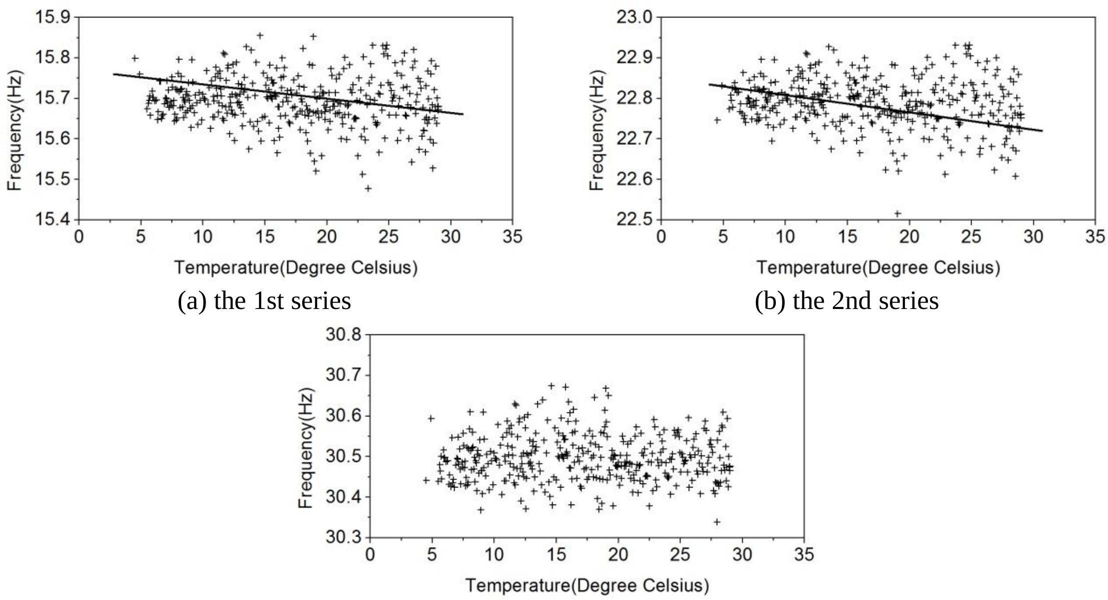
(c) the 3rd series

Fig. 11 Contribution of natural frequencies vs tourist number with respect to the tourist number using SSA. The correlation coefficient associates to the first three reconstructed series to the hourly averaged vibration are 0.36, 0.28 and 0.26 respectively, and the first series is more than that of other two reconstructed series.

The number of pedestrian may also affect the variation of the frequency. As mentioned in methodology part, the $\sqrt{\lambda_i}$ (i=1,...,d) are the singular values of matrix **X** and ratio $\lambda_i / \sum_{i=1}^{d} \lambda_i$ can be considered as the contribution of the matrix **X**i to the whole trajectory matrix **X**. The correlations between the contributions of the first three series and tourist numbers were analysed to reflect the variation of the contribution of natural frequency caused by pedestrian level, as shown in Fig. 11. From the figure, the raising number of tourists walking in the ancient building naturally induces an increase of the contribution of the first and third series. Thus, the correlation coefficient between the first reconstructed series and the hourly averaged vibration is highest, and this series plays a very important role in data analysis and the peaks of the spectra related with this series is easier excited by pedestrians.

3.3 Effects of temperature on natural frequencies

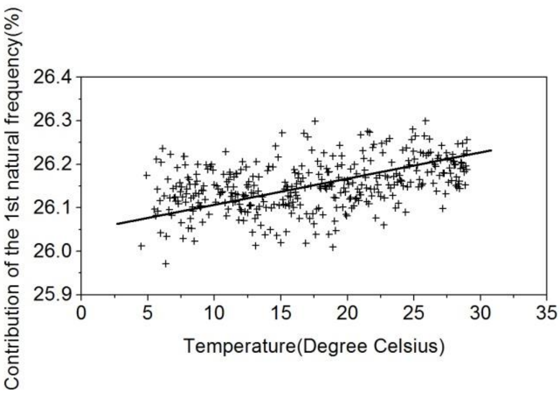
The temperature information during the measurement period was got from weather bureaus. Fig. 12 displays the relationship between temperatures and identified natural frequencies f1, f2 and f3, which demonstrates that all the first three modal frequencies of the building have a tendency to decrease with increased temperature. The second frequency is more sensitive to the temperature change than other frequencies, and the frequency decreases by approximately 0.55% with the temperature increase 25°C. From a continuous dynamic monitoring point of view, the relationship between temperature and the first two natural frequencies can be classified as linear while the third frequency does not show a linear downward trend.



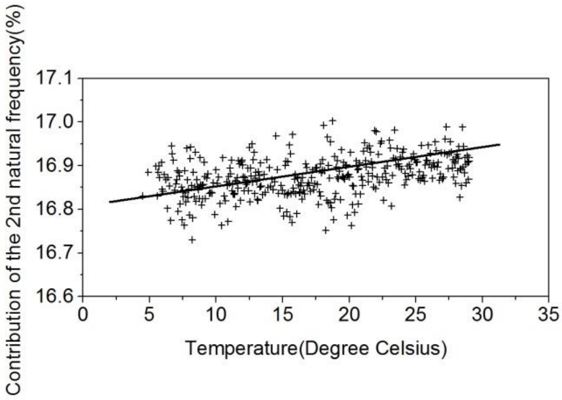
(a) the 1st series (b) the 2nd series

(c) the 3rd series

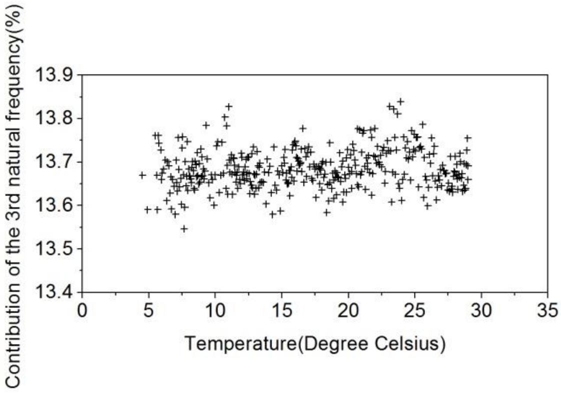
Fig. 12 Natural frequencies vs temperature



(a) the 1st series



(b) the 2nd series



(c) the 3rd series

Fig. 13 Contribution of natural frequencies vs temperature

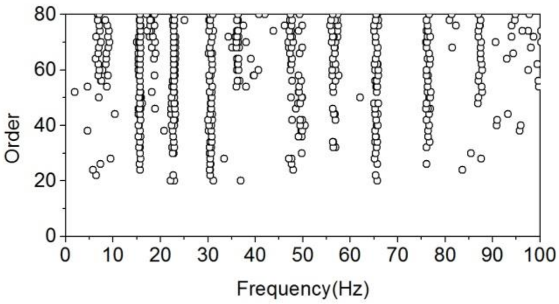
The correlations between the contributions of the first three series and temperature were also analysed to reflect the variation of the contribution of natural frequency, which can be seen in Fig. 13. With raising temperature, the contributions of the first two reconstructed series increase, which reflect the relations between temperature and the contributions of the first two natural frequencies analysed can be classified as linear.

3.4 Effects of earthquake loading on averaged acceleration and natural frequencies

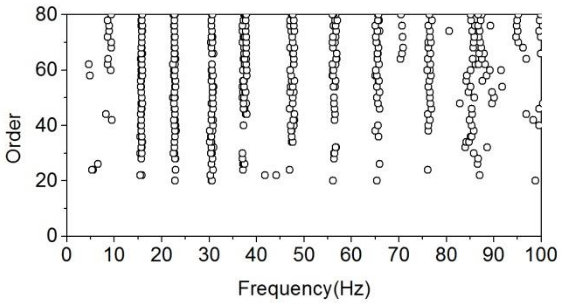
As previously described, nine large earthquakes occurred during the one year monitoring, and magnitudes of all earthquakes were greater than level 4. Fortunately, dynamic responses of the ancient building were monitored during the earthquake that occurred in 3 June 2013. In this section, data analysis would be done from two catalogues: using the measured dynamic data during earthquake and using the measured dynamic data before and after earthquake occurred.

Inspection of Fig. 5 shows the averaged acceleration amplitude in 3 June 2013 was much higher than other averaged acceleration amplitudes around that day while the number of tourists was less and the temperature was almost the same. The change is mainly due to earthquake loading. A stabilization diagram stemming using a covariance-driven stochastic subspace identification (SSI) technique was constructed to identify the modal properties in the earthquake occurred day, which can be seen in Fig. 14. The stabilization diagram shows that clear alignments of stable poles can be found in the frequency ranges 7-9 Hz and 17-18 Hz which is not obviously in normal days. The contribution of the first three series is less than that in normal days. When earthquake occurred, there are other frequency components in the dynamic responses.

Considering 30 days' acceleration data from 1 Sep 2013 to 30 Sep 2013, and three earthquakes occurred in this period, the impact of earthquakes on the fluctuations of the modal frequency are analyzed. Fig. 15 shows the identified three natural frequencies f1, f2 and f3 back to normal level after three earthquakes occurred. Considering the number of visitors and the temperature changes a little in this period, the stable variation of modal frequency reflects that earthquakes did not induce any damages in the ancient structure. At the same time, Fig. 16 shows the contribution of the first

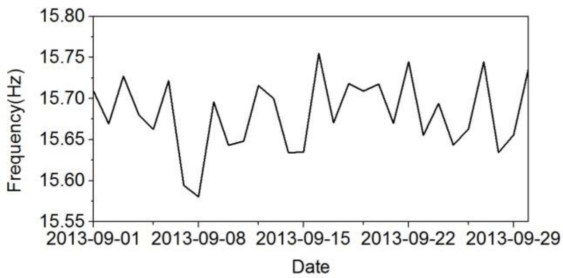


(a) Earthquake occurred day

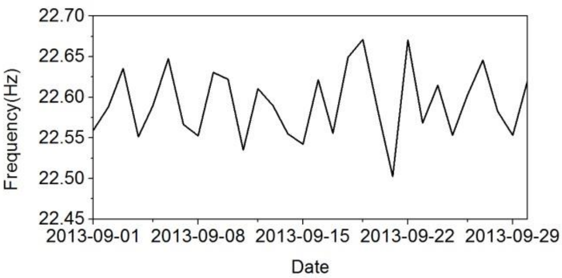


(b) Normal day

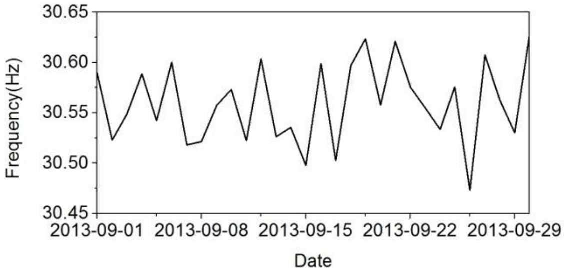
Fig. 14 Typical stabilization diagram produced by the SSI-COV technique



(a) the 1st series

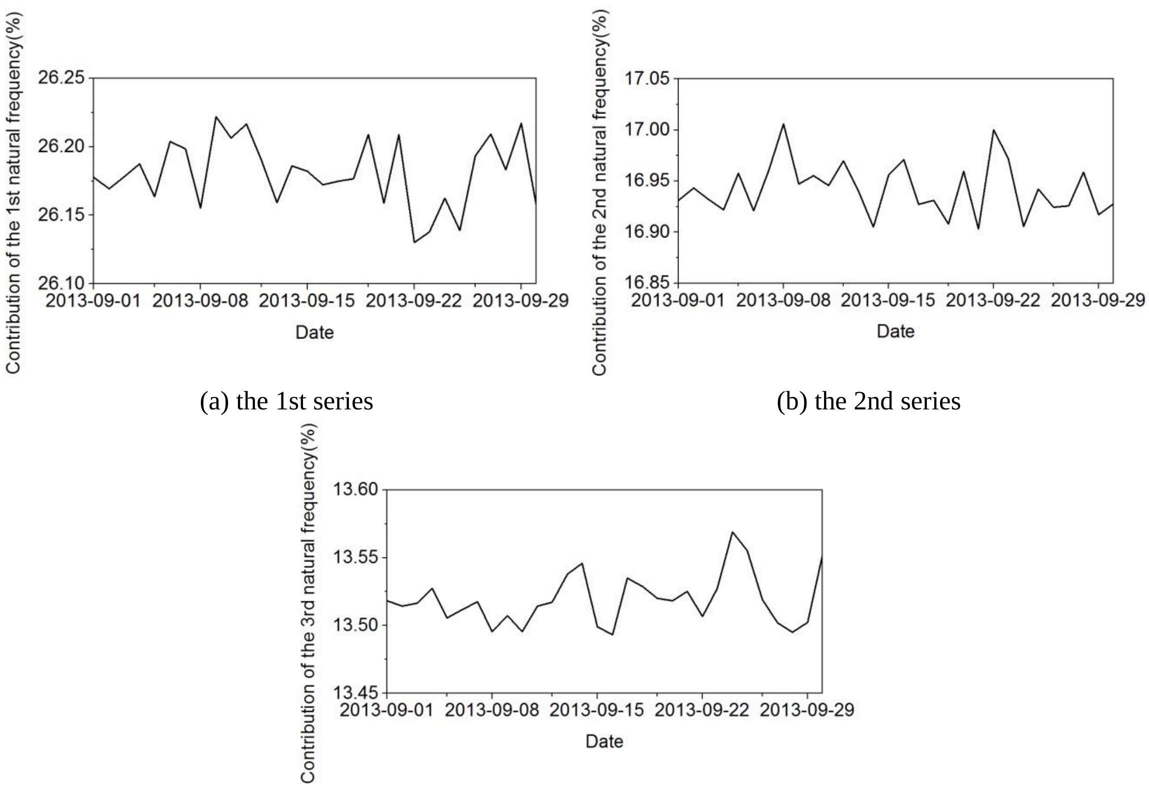


(b) the 2nd series



(c) the 3rd series

Fig. 15 Identified frequencies from 1 Sep 2013 to 30 Sep 2013



(a) the 1st series (b) the 2nd series

(c) the 3rd series

Fig. 16 Contribution of natural frequencies from 1 Sep 2013 to 30 Sep 2013

three series did not changed a lot, only there was a brief change from 22 Sep 2013 to 25 Sep 2013 and then backed to normal level. The time varying property during the earthquake may be due to the nonlinear behaviour of the building subjected to the strong ground motion. The time-varying parameters could be identified using the reduced extended Kalman filter technique by Ding *et al*. (2015). In this study, the frequencies do not have obvious changes before and after the earthquake, and the results show that the earthquake does not cause the structural damage.

4. Conclusions

This paper has introduced and described the substantial monitoring campaign being carried out on an ancient building in Tibet, China. This monitoring system had provided a wealth of high quality data continuously, and the effect of the earthquake and environmental factors has been analysed using Singular Spectrum Analysis (SSA) and Stochastic Subspace Identification (SSI).

The work covered has addressed which earthquake, environmental and operational conditions drive the fluctuations observed in the modal frequencies and the contribution of each natural frequency obtained from acceleration data by Singular Spectrum Analysis and then a covariance-driven SSI routine. Pedestrian loading was found to be a dominant driver of the first and third averaged acceleration series mostly, whose correlation coefficient to the hourly averaged vibration are 0.36, 0.28 and 0.26 respectively. Temperature was found to be classified as linear with the contributions of the first two natural frequencies. Lastly, when earthquake occurred, there would be found more frequency components in the spectra. The earthquake was found to have a significant effect on the modal frequencies at times but its impact on the structure can be recovered several days later.

It is demonstrated that such a dynamic monitoring system, apart from providing relevant instantaneous dynamic information and predicting the change in the first three modal frequencies to a good degree of accuracy, working as an alert system associated to the verification of vibration serviceability limits, can also serve as an effective tool for long term health monitoring.

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