Vibration Analysis of a High-Rise Building Under Construction - Study of a full-scale application

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Abstract: The focus of this paper is on vibration-based structural condition assessment of the central core walls of a 48-storey commercial building in Australia. This building is being renovated where part of the existing building is being demolished and reconstruction is being undertaken. The new building will be a hybrid building, with the original sections built in the 1970s followed by staged demolition and reconstruction. A structural health monitoring (SHM) network was installed during the demolition and reconstruction of the building, which records the vibrations produced during construction and ambient excitations including wind. This was undertaken assessing the safety and serviceability of the structure during the construction period. The vibrations were used to identify the frequency of the structure continually for over 3 years and reported on at fourteen specific stages. The analysis of the field measurement data has been done using the ambient vibration analysis in both the time domain and frequency domain and results are presented to compare the accuracy of different techniques.

Keywords: Structural Health Monitoring, High-rise buildings, Ambient vibrations, Construction, Frequency.

1. Introduction

Structural Health Monitoring (SHM) has become an emerging field in structural engineering in recent years, which controls the building safety, verifies and informs the changes in the condition of a structure to prevent catastrophic failures under extreme loading conditions, such as earthquakes and strong winds [1-5]. Thus, it is more commonly recommended that important buildings are continually monitored and evaluated on a regular basis with maintenances and rehabilitation made when it is necessary. Identifying damage in a structure is very important because early detection of damage can prevent catastrophic failure of the structure. The identification of damage without the need to demolish the structure using frequency or time responses has attracted many enthusiasts in the last decade, because the change in the physical properties of structures such as stiffness, mass, and damping ratio due to damage, alters the frequency and/or time responses of the structure.

In this project, considering the need to identify possible damage to the structure in the process of demolition and rebuilding, the issue of health monitoring of the core wall is of particular importance. Failure and defect in the shear wall structures can lead to serious damage or progressive failure of structures. Recently, several researches have been undertaken to improve the accuracy and reliability of SHM techniques, which systematically collect and analyze structural data to evaluate its status of health. In these methods, SHM is based on the fundamental idea that the dynamic properties of a structure are a function of its properties, so damage induced changes to the physical properties of the structure will invoke a change in its dynamic properties.

Recently, several studies have been carried out to improve the accuracy and reliability of the concept of SHM for fully constructed buildings by using a variety of methods [1-15]. Cawley and Adams were among the first to begin research in 1979 on frequency-based damage detection techniques. In this technique, damage detection is associated with a change in frequency, and changes in frequency are in turn due to changes in mass and stiffness, and other structural properties [8]. In 2001, Brincker [16] introduced a frequency domain technique for modal identification of output-only methods. In 2002, Kim and Melhem studied two concrete structures under fatigue loading and repeating shock. Applying Fourier transform and Wavelet, and by calculating the natural frequency before and after loading, they attempted to identify damage in concrete structures [9]. Yang in 2004 [17] presented a method of identifying the dynamic properties of a tall building by using ambient wind vibration data. He applied a Hilbert transform method to propose a SHM system for a 76-storey building polluted by noise and obtained remarkable results. In 2005, Lui and Ge carried out a research based on the Finite Element Model, using the dynamic properties of the structure, such as frequencies and modal shapes [10]. In 2012, Fu [18] conducted a full-field measurement due to wind effects on a super tall building in China and used power spectral density to evaluate the dynamic characteristics of the building. In 2012, Yan

[19], carried out ambient vibration measurement through Stochastic Subspace Identification (SSI) method, the Enhanced Frequency Domain Decomposition (EFDD) algorithm on a 610m high tower in China. Shi [20], performed the health monitoring of the Shanghai World Financial Center using both free and ambient vibration responses. They used the Peak-Picking method (PP) combined with the half power bandwidth and Hilbert-Huang transform methods. In 2016, Guo [21] proposed a near real-time hybrid framework for System Identification (SI) of structures.

Several researches have been undertaken on the vibrational analysis of buildings during the construction process. In 1996, Ventura researched the dynamic properties of a 30-storey reinforced concrete building by using ambient vibration methods [22]. In 2018, Park [23] presented a real-time structural health monitoring technique for a super tall building in Korea by using visual modal identification method and ambient vibration method.

The main purpose of monitoring a high-rise building during the construction process presented in this paper is to evaluate the properties of buildings under environmental conditions in multiple states of stiffness and mass and evaluating safety and serviceability of the building during demolition and reconstruction of the building from 2018 to 2021. The purpose of this paper is to compare the vibrational analysis methods for assessing the dynamic properties of a real building under the construction process from ambient vibration data. Two techniques for identifying the vibrational analysis were used. The frequency domain-based peak picking (PP) method and the time domain-based stochastic subspace identification (SSI) method.

2. Description of the Building

The existing building consists of a 48-storey commercial building constructed in the early 1970s, which included upper and lower ground levels, two basements for parking, and a concrete plant roof level. The floor slabs were partially demolished, and the remaining area was reinstated as part of a redevelopment that was refurbished.

3. Structural Health Monitoring System

The variations in the dynamic properties of the building were monitored during the partial demolition of the existing building and re-construction process at different stages over 3 years. A structural health monitoring system was installed to monitor the structural performance during the construction period and ensure that building dynamic properties are within the allowable limits, specified in the design process. For measuring the natural frequency of the building, acceleration of the building was measured using eight accelerometers distributed over the height of building, with three levels utilizing a pair of spatially separated accelerometers to allow separation of the torsional response from the sway components of each accelerometer. The remaining two levels include a single accelerometer for measurement of the sway response only. The levels selected to be instrumented were based on mode shapes provided by the Finite Element Model (FEM) which is not presented in this paper. To capture tower torsional response, it is preferable to install one accelerometer as close as possible to the center of rotation (CoR), and the second accelerometer radially as far as possible from the CoR.
The accelerometers utilized in this project were 3D wireless sensors which are MEMs-based sensors (Figure 1) capable of sampling up to 1000 Hz, though for the present implementation, the data is down-sampled to 10 Hz before transmission. The properties of the sensors are sensitivity: 660 mV/g, typical non-linearity: ±0.1% FS, noise spectral density: 45 μg/√Hz, Cross Axis Sensitivity: 2%.

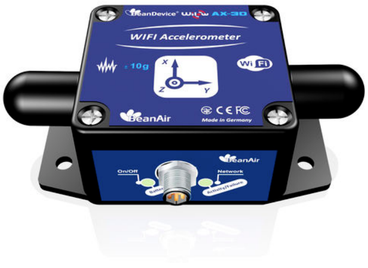

Figure 1 Wireless Accelerometer device installed on the core wall**.**

4. Output-only Modal Parameter Identification

In general, the task of structural health monitoring is conducted using one of three ways: (1) forced vibration testing, (2) free vibration testing; and (3) ambient vibration testing. Depending on the acceleration response of the structure and its magnitude, by choosing suitable accelerometers, natural vibration frequencies and main modal shapes of the structure can be measured for the long-term or short-term.

In forced vibration method, by applying different types of loadings onto structures that are carefully controlled, the response is collected. The main advantage of this method is that due to the relatively large loads, compared to the environmental and ambient loads, the effects of noise and error in the results will reduce. This method can also be used to locally stimulate the structure, making it easier to check the status of the system. In addition, the loading frequency can be determined in such a way that certain modes of the structure contribute more, leading to more precise results [14].

In ambient excitation testing, the structure's response to environmental factors such as wind, traffic, wave, etc. is used as stimulation. Therefore, this kind of excitation is more suitable for large structures that are difficult to excite or for long-term monitoring of structures. The main problem with this method is that the loading function is generally uncertain and may lead to inaccurate results.

For civil engineering structures, identification of the dynamic properties of the structures using outputs without measuring the inputs is one of the best techniques. Ambient vibration testing is a kind of output-only method, which has the advantage of being inexpensive without the need for artificial excitation. [15]

In this paper, two modal identification methods were implemented. The first method is the peak-picking (PP) method and the second one is the stochastic subspace identification (SSI) method.

• Peak-Picking Method (PP)

In 1993, the peak-picking method was proposed as one of the simplest methods to estimate the modal properties of a structure due to ambient vibration [24]. By observation of the peaks on the graph of Power Spectral Densities (PSDs), the natural frequency can be obtained. This method is based on discrete Fourier transform. PSDs are obtained by converting the measured accelerations from the time domain to the frequency domain using discrete Fourier transform (DFT).

• Stochastic Subspace Identification (SSI)

Currently, Stochastic Subspace Identification (SSI) is the most accurate and complete technique for identifying modal parameters of the output-only systems. De Moor and Overshcee published details of this technique in their book [25]. In 2000, Bart Peeters used SSI techniques to identify civil engineering structures in his doctoral dissertation [26]. Andersen and Brincker (2006) also explained the mathematical concepts used in the SSI technique more simply [27]. In this method, the dynamic behaviour of the white noise-excited structure is expressed using state-space equations. Then, system matrices are obtained using numerically powerful techniques such as Singular Value Decomposition (SVD) and the least-squares method.

The dynamic model of a structure can be expressed by a set of second-order linear differential equations with constant coefficients:

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

In Equation (1), C, M, and K are respectively mass, damping, and stiffness matrices of the structure, $\mathrm{U}(\mathrm{t})$ vector represents the displacement at all degrees of freedom of the structure, and $\mathrm{F}(\mathrm{t})$ is the vector of forces to the structure. Equation 1 can be rewritten in different ways in the form of a first-order differential equations system. One of the usual methods is to use state-space equations:

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

In this equation, the state vector equals $\mathrm{x}(\mathrm{t}) = [\mathrm{U}(\mathrm{t}) \quad \dot{\mathrm{U}}(\mathrm{t})]^{\mathrm{T}}$ and the state matrix $\mathrm{A_c}$and influence coefficients matrix of control system $\mathrm{B_c}$ are defined as follows:

$$F(t) = B_2 u(t) \tag{3}$$

$$B_c = \begin{bmatrix} 0 \\ M^{-1} B_2 \end{bmatrix}$$

$$A_c = \begin{bmatrix} 0 & I \\ -M^{-1} K & -M^{-1} C \end{bmatrix}$$

Similarly, the output vector $y(t)$ can be interpreted as a linear combination of system states:

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

In the above equation, C is the actual output influence coefficients matrix and D is the output control influence coefficients matrix. From the combination of Equation (3) and Equation (4), the continuous-time state-space model of a system is obtained. The time-continuity of this model means that these equations can be obtained at any time. Of course, this assumption is not correct because the data obtained from the vibration test are discrete. The continuous-time state-space model can be converted into a discrete-time form as follows:

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

$$y(t) = Cx_k + Du_k \tag{6}$$

In this equation, $x_k = x(k+t)$ is the time-discrete vector and $A = \exp(k+t)$ is the system matrix in the discrete-time state. $B = [A - I]A_c^{-1}B_c$ is also the discrete input matrix. Equation (5) and Equation (6) describes a discrete-time state-space model of the dynamical system. In practice, there are always uncertainties, including measurement and computational noises. Computational noise is caused due to modelling errors and measurement noise due to sensor errors and environmental errors. Given the computational noise w_k and measurement noise v_k, the above equations can be corrected as follows:

$$x_{k+1} = Ax_k + Bu_k + w_k \tag{7}$$

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

Since it is difficult to achieve the correct characteristics of measurement and computational noises, we use some simplifying assumptions. It is assumed that both measurement and computational noises are white noise with a mean of zero and their covariance matrices are defined as:

$$E\left[\begin{pmatrix} w_p \\ v_p \end{pmatrix}\begin{pmatrix} w_q^T & v_q^T \end{pmatrix}\right] = \begin{pmatrix} Q & S \\ S^T & R \end{pmatrix}\delta_{pq} \tag{9}$$

In this equation, E is the expected value, and δ_{pq} the Kronecker delta. It is also assumed that v_k and w_k are statistically independent of each other.

In the ambient vibration test, the input is unknown; therefore, by removing u_k in Equation (7) and Equation (8), the following equation is achieved:

$$x_{k+1} = Ax_k + w_k \tag{10}$$

$$y_k = Cx_k + v_k \tag{11}$$

According to Equation (9), the input data is modelled by the noise terms v_k and w_k; however, the assumption that these terms are white noise and cannot be ignored, but this assumption is not practically correct, for example, the input contains the components other than white noise or has a few dominant frequencies, then these frequencies cannot be separated from the special frequencies of the system and represent themselves as matrix poles of system A.

System identification is performed by ambient vibration tests in the time domain based on Equation (10) and Equation (11). There are several methods for implementing the system identification according to Equations (10-11). The SSI method is currently the most advanced known method for identifying the system through ambient vibration testing. The SSI method obtains the state-space matrices using powerful mathematical tools such as the SVD and the least-squares method. After calculating the state matrices, modal parameters are obtained by decomposing the special values of these matrices.

In all systems identification methods using ambient vibration testing, there is no normalizing scale for known modal shapes due to the immeasurability of the input. In other words, modal shapes cannot be normalized relative to mass.

4. Results of the structural monitoring

Several challenges were faced in the ambient vibration analysis of building during the construction and demolition process. One of them was related to construction activity like concrete pouring/pumping, crane working on-site, and also the continuous variation of building properties which show the importance of data filtering in vibrational analysis. For the filtering process, data were divided into groups of 10-minute intervals and in each time window bandpass filtering was applied to remove the effect of high-frequency noises and focus on the first couple of modes only.

Using the natural excitations as the input to the building, like the wind, is a random process. Therefore, measuring the pressure of wind fluctuations on the windward and leeward faces from fluctuations in wind velocity, and its interaction with the structure, results in a long-wind motion for the building, and plays a major role in the monitoring process of the building. In addition to that, one of the special problems that need to be considered was that wind loads on a group of super tall buildings in a real environment were different from those on an isolated building. Hence, the proper evaluation of wind pressure had a great significance to understand the effects of winds on this building, and one anemometer was deployed at the top of a nearby structure (200 m) to monitor the speed and direction of wind.

Acceleration responses are presented in Figures 2 and 3 for two consecutive days with different wind speeds and the difference in acceleration amplitude on a windy day and non-windy day from time history is observed.

The vibrational modal identification was accomplished using both the peak picking technique and the SSI method in MATLAB [28] software.

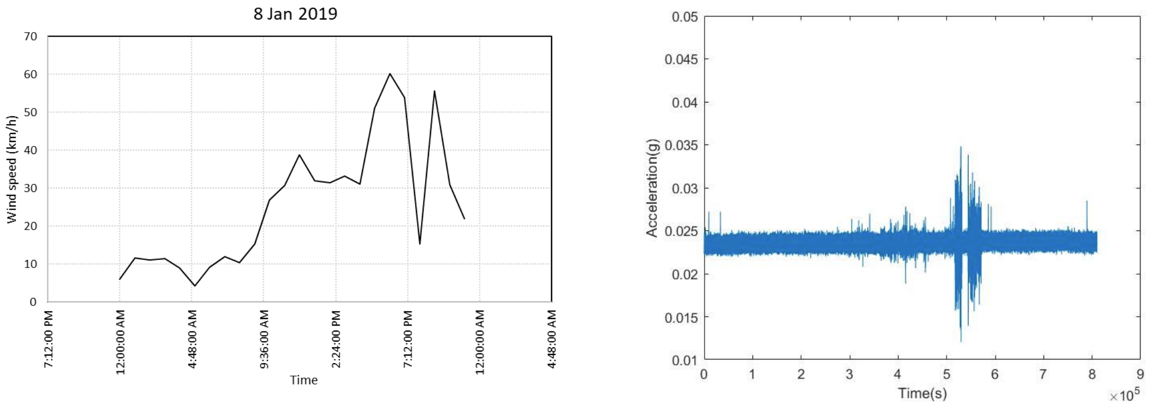

Figure 2 Daily variation in the accelerations with respect to the wind speed on a windy day.

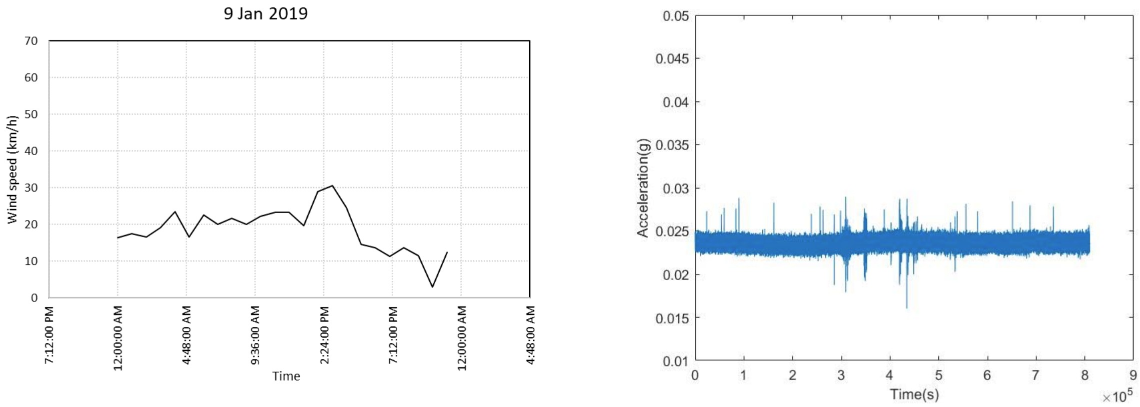

Figure 3 Daily variation in the accelerations with respect to the wind speed on a non-windy day.

The average normalized value of frequency using the PP method is presented in Figure 4, while Figure 5 shows the frequency result of the building obtained by SSI corresponding to data of one sensor on top floor of the building. The frequency of 0.28 Hz, detected by the SSI method, is clearly obtained in the PP. Figure 6 presents the average of obtained frequency among different time windows.

Figure 7 shows the variation of the natural period according to the construction period during demolition and reconstruction. The variation in this graph shows the effect of construction stages by changes in the building properties such as mass and stiffness over 3 years.

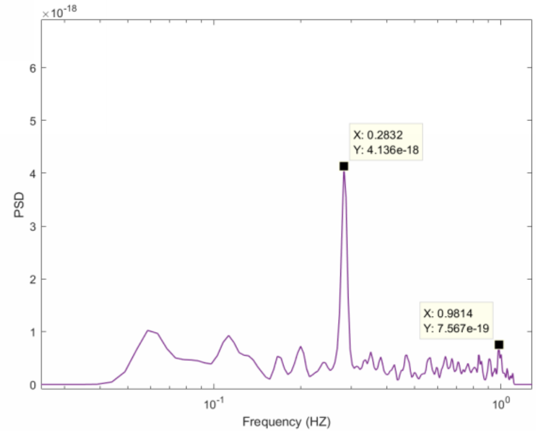

Figure 4 PSD of acceleration signal at stage 2 (Demo down to L40).

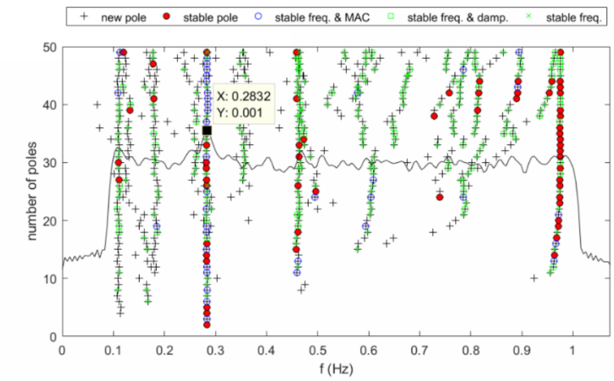

Figure 5 Stabilization diagram of SSI at stage 2 (Demo down to L40).

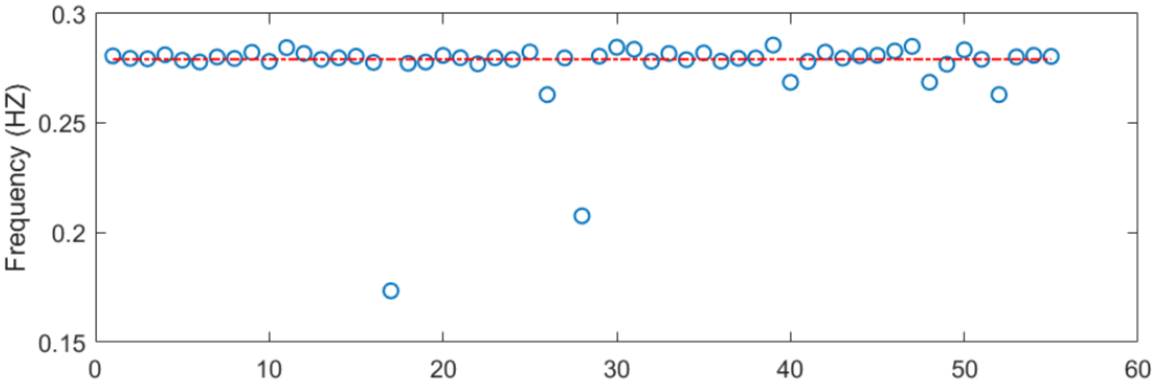

Figure 6 Stabilization diagram of SSI at stage 2 (Demo down to L40).

5. Conclusions

The ambient vibration method has been used for a full-size building during construction work to estimate the building modal properties. Two independent techniques were deployed, noise was filtered and the most continuous variation of dynamic property of the building has been obtained. A good agreement in the identification of natural frequency has been obtained with the PP method and the time domain SSI method. The information measured by the monitoring system allowed for the continued verification of the construction progress.

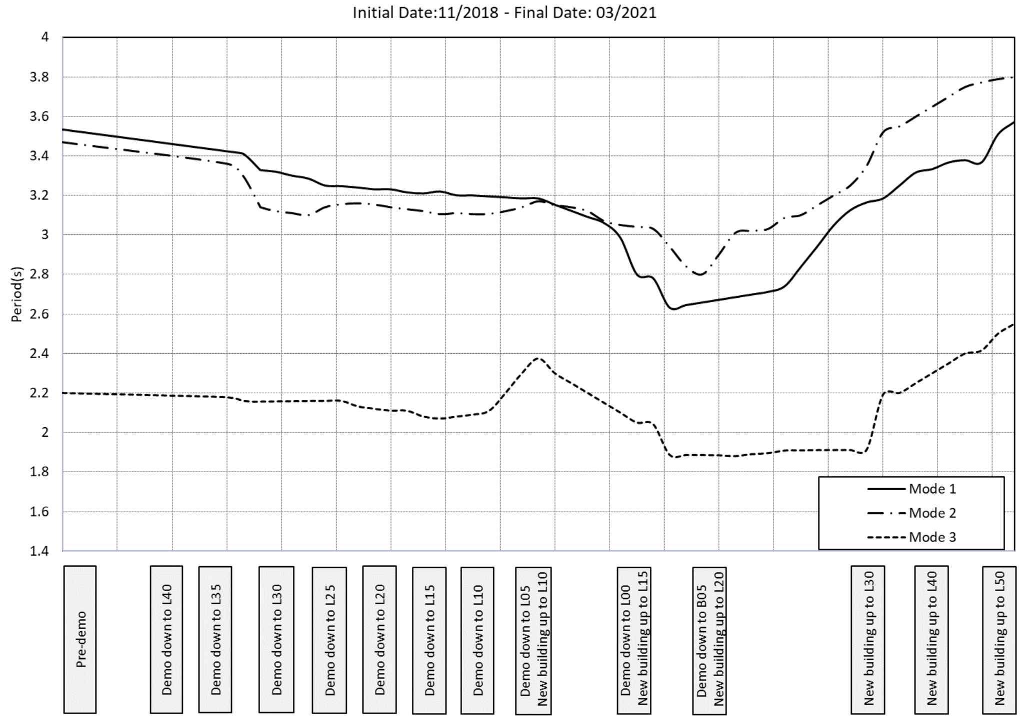

Figure 7 Period variations during the monitoring period.

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7. References

1. Boroschek, R., Nunez, T., and Yanez, T. (2010a). “Development of a real time Internet based monitoring system in a nine story, shear wall building.” Proc. of the 14th European Conf. on Earthquake Engineering.
2. Celebi, M., and Liu, H.-P. (1998). “Before and after retrofit—Response of a building during ambient and strong motions.” J. Wind Eng. Ind. Aerodyn, 77–78, 259–268.
3. Celebi, M., Sanli, A., Sinclair, M., Gallant, S., and Radulescu, D. (2004). “Real-time seismic monitoring needs of a building owner and the solution.”Earthq. Spectra, 20(2), 333–346.
4. Ni, Y., Chia, Y., Liao, W., and Ko, J. (2009). “Technology innovation in developing the structural health monitoring system for Guangzhou new TV tower.” Struct. Contr. Health Monit., 16(1), 73–98.
5. Peeters, B., and De Roeck, G. (1998). “System identification and damage detection in civil engineering.” Ph.D. thesis, Faculteit Toegepaste Wetenschappen, Katholieke Univ. Leuven, Belgium.

6. Peeters, B., and De Roeck, G. (2000). “One-year monitoring of the Z24- bridge: Environmental influences versus damage events.” Proc., 18th IMAC Conf., Katholieke Univ. Leuven, Leuven, Belgium.
7. Peeters, B., and Ventura, C. E. (2003). “Comparative study of modal analysis techniques for bridge dynamic characteristics.” Mech. Syst.Signal Process. 17(5), 965–988.
8. Cawley P, Adams RD. “The location of defects in structures from measurements of natural frequencies”. The Journal of Strain Analysis for Engineering Design. 1979 Apr 1;14(2):49-57.
9. Melhem H, Kim H. “Damage detection in concrete by Fourier and wavelet analyses”. Journal of Engineering Mechanics. 2003 May;129(5):571-7.
10. Ge M, Lui EM. “Structural damage identification using system dynamic properties”. Computers & structures. 2005 Oct 1;83(27):2185-96.
11. Sasmal S, Ramanjaneyulu K. “Detection and quantification of structural damage of a beam-like structure using natural frequencies”. Engineering. 2009 Nov 24;1(03):167.
12. Yan S, Sun W, Song G, Gu H, Huo LS, Liu B, Zhang YG. “Health monitoring of reinforced concrete shear walls using smart aggregates”. Smart materials and structures. 2009 Mar 9;18(4):047001.
13. He K, Zhu WD. “Structural damage detection using changes in natural frequencies: theory and applications”. In Journal of Physics: Conference Series 2011 (Vol. 305, No. 1, p. 012054). IOP Publishing.
14. Kodikara KA, Chan TH, Nguyen T, Thambiratnam DP. “Model updating of real structures with ambient vibration data”. Journal of Civil Structural Health Monitoring. 2016 Jul 1;6(3):329-41.
15. Ren WX, Zong ZH. “Output-only modal parameter identification of civil engineering structures”. Structural Engineering and Mechanics. 2004 Mar 1;17(3-4):429-44.
16. Brincker, R., Zhang, L. and Andersen, P., 2001. “Modal identification of output-only systems using frequency domain decomposition”. *Smart materials and structures*, *10*(3), p.441.
17. Yang JN, Lei Y, Lin S, Huang N. “Identification of natural frequencies and damping’s of in situ tall buildings using ambient wind vibration data”. Journal of engineering mechanics. 2004 May;130(5):570-7.
18. Fu, J.Y., Wu, J.R., Xu, A., Li, Q.S. and Xiao, Y.Q., 2012. “Full-scale measurements of wind effects on Guangzhou West Tower”. *Engineering Structures*, *35*, pp.120-139.
19. Shi, W., Shan, J. and Lu, X., 2012. “Modal identification of Shanghai World Financial Center both from free and ambient vibration response”. *Engineering Structures*, *36*, pp.14-26.
20. Guo, Y., Kwon, D.K. and Kareem, A., 2016. “Near-real-time hybrid system identification framework for civil structures with application to Burj Khalifa”. *Journal of Structural Engineering*, *142*(2), p.04015132.
21. Ventura, C., and Schuster, N. (1996). “Structural dynamic properties of a reinforced concrete high rise building during construction.” Can. J. Civil Eng., 23(4), 950–972.
22. Park HS, Oh BK. “Real-time structural health monitoring of a supertall building under construction based on visual modal identification strategy”. Automation in Construction. 2018 Jan 1;85:273-89.
23. Felber AJ. Development of a Hybrid Bridge Evaluation System, 277 p (Doctoral dissertation, PhD Thesis, University of British Columbia).
24. Newland DE. Random Vibrations, Spectral & Wavelet Analysis. Longman Scientific & Technical. 1993.
25. Van Overschee P, De Moor BL. Subspace identification for linear systems: Theory Implementation—Applications. Springer Science & Business Media; 2012 Dec 6.
26. Peeters B, De Roeck G. Reference-based stochastic subspace identification for output-only modal analysis. Mechanical systems and signal processing. 1999 Nov 1; 13(6):855-78.
27. Brincker R, Andersen P. Understanding stochastic subspace identification. Proceedings of the 24th IMAC, St. Louis. 2006 Feb;126.
28. Matlab software pachages, 2019.