Signal processing techniques for structural health monitoring of super high-rise buildings

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Abstract. Along with the accelerating urbanization and the increasing population density, large numbers of super high-rise buildings have been built around the world in the past decades. Together with the successive construction of these buildings, the structural safety issues have received more and more attention from all walks of life. During the operation period of super high-rise buildings, the long-term effects of environmental degradation and abnormal loads usually lead to the occurrence of damages in local areas of the building structure, which after continual accumulation, would inevitably cause the degradation of structural performance, or even structural failures, severely threatening life and property to the country and people. Therefore, various structural damage identification techniques are applied to conduct structural health monitoring (SHM) for super high-rise buildings that under construction and completed in order to discover possible structural damages in time, and carry out safety assessments with disaster warnings for possible dangers and unfavorable conditions of the structures for determination of reasonable and economic maintenance periods. This paper gives a brief review on the existing signal processing techniques used for damage identification and SHM of super high-rise buildings, and further summarizes the future research trend of these techniques.

1. Introduction
In the wake of serious shortage of urban land resources in recent decades, construction of super high-rise buildings has become one of the mainstream development direction of modern construction industry. Up to now, over 4674 super high-rise buildings whose height reaches 150 m or more have been built all over the world. Along with the successive construction of these buildings, the structural safety issues have received more and more attention from all walks of life. During the operation period of super high-rise buildings, the long-term effects of environmental degradation and abnormal loads usually lead to the occurrence of damages in local areas of the building structure, which after continual accumulation, would inevitably cause the performance degradation, or even failures of the structure, severely threatening life and property to the country and people. Therefore, it is of great significance to implement structural damage identification and structural health monitoring (SHM) on super high-rise building structures in order to detect possible structural damage in time, to guarantee structural safety, and to issue early warning for possible dangers and unfavorable anomalies of structures[1].

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2. SHM applications in super high-rise buildings

SHM aims to track and evaluate events, abnormalities, degradation or damage during operation of a structure by measuring the operating and loading environment and crucial responses of the structure to give a diagnosis about the state of the structure at each moment during its lifetime. It first emerged in aerospace field for evaluation of the impact of loading on a structure during its operation period[2]. Later, SHM techniques were widely applied in multiple engineering fields, such as bridges[3-4], offshore jacket platforms[5], and submarine pipe-lines[6]. Along with the evolution of intelligent sensors and wireless sensor technologies, they have been gradually applied in the field of super high-rise buildings[7-10]. For example, Ni et al.[7] designed a sophisticated SHM system which integrates in-construction and in-service monitoring, and implement it on the Guangzhou New TV Tower (GNTVT). Su et al.[8] employed a GPS-based SHM system for both in-construction and in-service real-time monitoring of the Shanghai Tower. Li et al.[9] installed a wind and movement monitoring system on the Hong Kong International Finance Center building to study the wind effect, dynamic characteristics and the serviceability performance of the building during the typhoons. Xiong et al.[10] employed Real Time Kinematic - Global Navigation Satellite Systems (RTK-GNSS) sensors on the Tianjin 117 high-rise building to study the dynamic properties of the building under construction.

Despite the large advancement of SHM techniques for super high-rise buildings, further studies and development are still in urgently need, since few full-scale monitoring data about the dynamic properties of the buildings under service conditions have been developed for super high-rise buildings[11].

3. Signal processing techniques used in SHM of super high-rise buildings

Among various structural damage identification techniques, signal processing techniques are a class of indispensable means of structural health monitoring technology. Various researches have been carried out on structural damage identification by means of signal processing techniques, some of the most popular of which for SHM of super high-rise buildings are reviewed as follows:

3.1. Statistical time series models

As the earliest models used in SHM, statistical time series (TS) models are proposed to develop approximate models based on input-output measurements, which can be usually classified into two classes: linear and nonlinear statistical TS models. The most popular linear statistical TS models are autoregressive (AR) model, moving-average (MA) model, autoregressive moving average (ARMA) model, together with their variations: autoregressive vector (ARV) model, autoregressive model with exogenous inputs (ARX), and autoregressive integrated moving average (ARIMA). By adoption of ARMA model, Nair et al. [12] proposed a damage-detection algorithm to detect and locate damages in the ASCE benchmark structure of a four story, two-bay x two-bay steel-braced frame, in which they found that the most robust damage-sensitive feature (DSF) is defined by the first AR coefficient normalized by the square root of the sum of the squares of the first three AR coefficients. Gislason [13] proposed an ARMA with exogenous inputs for the damage identification, quantification and localization of multi-story steel and reinforced concrete structures under multiple damage scenarios.

Although linear statistical TS models are the most utilized models, yet they still have limitations since they are not capable of modelling noise-contaminated measured structural responses and the complicated nonlinear dynamic properties of civil structures[14]. To handle these limits, nonlinear statistical TS models, such as nonlinear autoregressive with exogenous inputs (NARX) models, and nonlinear autoregressive moving average with exogenous inputs (NARMAX) models are used as instead.

3.2. Fast Fourier transform

The most commonly used signal processing technique is Fourier transform (FT) based spectrum analysis. With the help of Inverse FT, a signal is expressed as the superposition of complex exponentials of various frequencies with complex amplitudes defined by FT. One of the most popular
FT based diagnosis techniques for discretized time signals is Fast Fourier Transform (FFT), which, as one of the oldest methods for signal processing in SHM, has been used for damage identification of various types of structures. For example, Mahapatra and Gopalakrishnan[15] took the advantage of FFT algorithm coupled with Finite Element analysis to study the effect of wave scattering and power flow through multiple delaminations and strip inclusions in composite beams with general ply stacking sequence. Cheraghi et al.[16] proposed an approach to evaluate the damage energy indices of pipes based on FFT algorithm. Xu and Wu[17] presented an acceleration responses’ energy-based damage detection strategy for a long-span cable-stayed bridge with the help of FFT. Hsu et al.[18] installed a wireless sensing system on a scaled six-story steel building structure under El Centro earthquake excitation, which used FFT algorithm for determination of measured frequencies. Amerzquita-Sanchez et al.[19] adopted FFT for modal parameter identification of a five-bay space truss structure under earthquakes, traffic-induced vibrations and Chirp signal-generated excitation. DeVore et al.[20] applied FFT to implement Frequency Response Function estimation in a substructure identification estimator for identification of the story-level stiffness of a four-story shear building.

The application of FFT requires that the system to be analysed must be linear and the data to be processed must be strictly periodic or stationary, yet due to the lack of alternatives, it is still widely used for finite-duration and nonstationary data. Misleading results might be obtained by uncritical application of FFT and casual adoption of the stationary and linear assumptions[21].

3.3. Short-Time FT
Since Fourier basis functions are localized in frequency but not in time, an alternative method naming the Short-Time FT (STFT) was proposed by Denis Gabor[22], who multiplied a signal by a pre-fixed window function which is nonzero for only a short period of time, then took the FT of the modified signal when the window was sliding along the time axis, resulting in the sinusoidal frequency and phase content of sections of the signal. STFT conquers the problems of FFT and is capable to analyse non-stationary signals. Portnoff[23] developed a representation for discrete-time signals and linear time-varying (LTV) systems based on STFT and the time-varying frequency response. Based on Portnoff’s work, Kozek[24] presented a time-frequency processing approach using the Weyl symbol to study the time-frequency properties of LTV systems. Benisty et al.[25] proposed a Time-varying STFT for discrete signal representation. STFT techniques were also used in damage identification of buildings. For example, Dong et al.[26] employed STFT in the structural damage detection of a 7-story RC building under the 1994 Northridge earthquake. Nagarajaiah and Basu[27] developed STFT based technique for modal identification and structural damage detection of a three story scaled building model.

However, due to the limit of the Heisenberg uncertainty principle, the trade-off between time and frequency resolution of STFT is unavoidable, which largely limits the application of STFT and requires the advent of alternative time-frequency analysis methods.

3.4. Wigner-Ville distribution
Wigner-Ville distribution (WVD) is an effective method mostly used to process nonlinear signals of civil structures, which can estimate instantaneous frequency at each data point with a typical temporal resolution of fractions of a second. Bradford et al.[28] applied WVD to detect damage in a 20-story steel moment-frame building under strong ground motions by analyzing the evolution of frequency content of measured signals. Michel and Guéguen[29] used smoothed reassigned pseudo-Wigner-Ville method to follow the non-linear evolution of the resonance frequencies of a 13-story RC-structure under weak earthquakes.

Despite the good resolution in the time-frequency domain and easy implementability of WVD, it exhibits two general drawbacks, the first of which is that it often gains negative values in certain regions of the time-frequency plane that makes the physical interpretation quite problematic, and the second of which is the unavoidable cross-term interference that corrupts the time-frequency representation severely and induces poor resolution in the WVD for many practical cases[30]. Many
efforts has been devoted to solve this problem. For example, Qian and Chen[31] proposed the adaptive Gaussian basis representation (AGR) and combined it with WVD to develop an adaptive spectrogram that is a non-negative, cross-term free signal energy distribution with high resolution. Based on their work, Spanos et al.[32] derived adaptive chirplet spectrograms to detect damage in a 20-story steel frame under seismic excitations.

3.5. WT
WT is a multi-resolution analysis method which represents a signal by the superposition of its projections on a set of daughter wavelets generated by scaling and translating a priori fixed mother wavelet in both time domain and frequency domain. By adoption of a mother wavelet that is both shifted and dilated, WT mitigates the limitations of FT and STFT. Furthermore, it uses time window shorter than that of the STFT, which yields accurate signal spectrum and thus can implement faster model variation detection. It has emerged in the field of civil engineering as a significant tool for structural damage identification in recent years. For example, Solis et al.[33] proposed a combined modal-wavelet analysis for crack location in beams, which used a continuous wavelet transform (CWT) to identify changes in mode shapes induced by damage. Amezquita-Sanchez and Adeli[34] presented a new synchrosqueezed wavelet transform–fractality dimension method for damage detection, localization and quantification in a 1:20 scaled model of a 38-storey concrete building structure.

Like STFT based methods, WT based methods are methods with a pre-fixed basis, which have difficulty in application to the identification of system parameters[35] and usually give instantaneous modal parameters only. And as mentioned above, in light of the limit of Heisenberg uncertainty principle, WT based methods cannot simultaneously have the time and frequency resolutions with the same precision.

3.6. HHT
To conquer the limitations of STFT and WT, Huang et al. proposed an adaptive based method, the Hilbert-Huang transform (HHT), which is the combination of Empirical mode decomposition (EMD) and Hilbert transform (HT)[21]. With the help of intrinsic mode functions (IMFs) obtained by application of EMD to any nonlinear and non-stationary signals, the instantaneous dynamic properties of the signals can be captured both in time and frequency domain, which also overcomes the limits of FFT. In the past two decades, HHT has been widely used in many applications. For example, Bahar and Ramezani[36] applied an HHT based method to identify modal frequencies of a real 15-story steel-frame building. Xu et al.[37], Yang et al.[38], Li et al.[39] as well as Shi et al.[40] respectively used HHT based methods to carry out modal parameter identification of super high-rise buildings with time invariant physical parameters, such as the Di Wang Building, a Melbourne concrete office building, the GNTVT, and the Shanghai World Financial Center. HHT based methods have been also applied by Shi and Law[41], Hu and Proppe[42] for parameters identification of multi-degrees-of-freedom shear-beam building models with LTV physical parameters.

Although HHT is a powerful tool in many applications, it still has some unresolved drawbacks, such as the mode mixing effect, which often occurs when signals of different time scales are mixed in one IMF or a signal of a similar time scale appears in different IMF components. In order to remove the mode mixing effect without using the intermittency test proposed by Huang et al.[43], Wu and Huang[44] proposed the ensemble EMD (EEMD) method. Based on their work, Sadhu[45] developed a hybrid EMD method, which combines a multivariate EMD with EEMD for resolving mode mixing issues to implement modal identification of a 5-storey shear-beam structure model and a six-storey steel frame experimental model.

3.7. Integrated methods
As the aforementioned signal processing techniques have their respective advantages and dis advantages, it is preferable to integrate the techniques in order to avoid each other’s deficiencies. Yi et al. [46] adopted a combination of EMD method and WT to study the dynamic characteristics of the
88-story Hong Kong International Finance Center building during typhoons. Li et al. [47] presented a new method based on the integration of discretized synchrosqueezed wavelet transform, the Hilbert transform, and the linear least square fit to identify modal parameters of the 123-story Lotte World Tower. As Bayesian inference is a powerful tool for uncertainty quantification and updating, many researchers tried to combine it with other techniques for damage identification of building structures. Au[48] proposed the Fast Bayesian FFT (FBFFT) method for modal identification of a 6-story shear building and a super tall building in Hong Kong. Later, Zhang et al.[49], Qing et al.[50] as well as Huang et al.[51] respectively applied FBFFT method for modal parameter identification of GNTVT, Shanghai Tower, and the 68-story Cullinan residential towers in Hong Kong.

4. Conclusion
Some of the most popular signal processing techniques for SHM of super high-rise buildings, such as statistical TS models, FFT, STFT, WVD, WT, and HHT are reviewed in this paper. In applications of damage identification of super high-rise buildings, it is more preferable and promising to integrate any two or several above techniques, so that we can make use of the merits with avoidance of the deficiencies of individual techniques. Furthermore, together with rapid development of the intelligent sensor techniques, wireless sensing technologies, mobile wireless sensing technologies, image recognition technology, virtual reality technology, big data technology, cloud technology as well as model updating theories, reliability theory and safety evaluation methods, future trend of SHM techniques of super high-rise buildings might be integrating the existed signal processing techniques with several of the above intelligent techniques for automatic damage detection out of massive monitoring data. The authors are aware of the nonexistence of a universal technique for all applications, and this paper concludes the possible future research trend of damage identification techniques and SHM techniques of super high-rise buildings for engineers and researchers.

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