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REVIEW ARTICLE

The State-of-the-Art on Time-Frequency Signal Processing Techniques for High-Resolution Representation of Nonlinear Systems in Engineering

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Abstract

One of the serious issues of traditional signal processing techniques in analyzing the responses of real-life structures is related to the presentation of fundamental information of nonlinear, non-stationary, and noisy signals with closely-spaced frequencies. To overcome this difficulty, numerous studies have been carried out recently to explore proper time-frequency signal processing techniques to efficiently present high-resolution representations for nonlinear characteristics of analyzed signals. Despite existing extensive reviews on vibration-based signal processing techniques in time and frequency domains for Structural Health Monitoring purposes, there exists no study in categorizing the signal processing techniques based on the feature extraction with time-frequency representations. To fill this gap, this paper presents a comprehensive state-of-the-art review on the applications of time-frequency signal processing techniques for damage detection, localization, and quantification in various structural systems. The progressive trend of time-frequency analysis methods is reviewed by summarizing their advantages and disadvantages, as well as recommendations of combination methods to be utilized for different applications in various complicated structural and mechanical systems.

1 Introduction

With increasing urbanization and construction of civil engineering structures such as building, bridges and dams, etc. dependency on and needs for structural health monitoring (SHM) of various structural systems are growing when subjected to natural disaster such as earthquake, flooding and other catastrophes or under weakening environmental factors leading to deterioration such as such as humidity, salinity, atmospheric acidity, scour, and wind. The analysis of nonlinear and non-stationary signal responses of different structural [1–6] and mechanical [7–12], systems especially real-life structures exposed to various dynamic loads and noisy environments always challenges traditional signal processing techniques with time-domain or frequency-domain representations for damage detection, localization, and quantification purposes. Traditional signal processing techniques have serious deficiencies in the analysis of nonlinear and noisy signals that contain closely-spaced frequencies. Therefore, utilizing robust signal processing techniques to capture the nonlinear properties of vibration response of structures is of paramount importance in damage localization, quantification, and detection process [13]. Hence, many attempts have been made in recent decades to improve the performance of signal processing techniques by proposing time-frequency analysis approaches that are efficiently able to capture the fundamental information of analyzed signal with high-resolution representations. The successful performance of time-frequency signal processing approaches have been extensively reported by previous studies, especially for SHM of real-life structures representing noisy signals with nonlinear characteristics. These techniques are even efficiently able to identify invisible damages

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occurred in the internal section of the structures through the variation of nonlinear structural characteristics. Despite existing several review studies in the literature on vibration-based structural damage detection approaches, there exists no review in categorizing the applications of signal processing techniques with time-frequency representations. This paper presents a comprehensive review on the development of time-frequency signal processing techniques in recent decades. The applications of time-frequency analysis techniques in various scientific fields of aerospace, civil, and mechanical engineering are reviewed by clarifying their advantages and deficiencies.

2 Short Time Fourier Transform (STFT)

To overcome the drawbacks of Fast Fourier Transform (FFT) technique as a traditional signal processing technique in the presentation of spectral time-variations, an extension technique named short time Fourier transform (STFT) introduced by Gabor [14] that can efficiently represent the frequency contents in time domain. STFT is known as an alternative and improved FFT technique that can effectively analyze non-stationary signals. That is, this techniques is able to capture the local frequencies occurred during very short time periods in the response vibrations that cannot be recognized using FFT. The procedure of recognizing the instant local frequencies over the time using the STFT is based on dividing the signal time history response into short time intervals (i.e., time windows) each of which is analyzed using the FFT in frequency domain during the specified short time period of each window [15]. The STFT is mainly employed to identify the time-frequency representation of the vibration responses of structures due to its capability in presenting more understandable information along with useful definitions of the time-frequency distributions of the analyzed signals. The STFT technique has been widely used in the literature for identifying the modal parameters of different structures such as reinforced concrete (RC) frames [16], steel frames [17], truss-type structures [18], and beam members [19]. One of the main shortcomings of the STFT is related to the dependency of its accuracy and the resolution of its results on the analyzed window size. As such, to capture high-resolution frequency results and identify the information of closed natural frequencies, the time window size should be sufficiently large [20]. However, the behavioral trend of transient signals is efficiently estimated through the analysis of large-size time widows. Figure 1a and b illustrate examples of the time-frequency distributions of the acceleration record of El Centro earthquake (1940, N–S) and analyzed vibration responses of a 7-story RC framed building under this earthquake obtained in terms of the daily length of day data [16].

Yesilyurt and Gursoy [19] employed STFT technique to identify the modal damping ratios of a composite beam. However, the modulus information of this member including the Young’s modulus in fiber direction, shear modulus, and transverse Young’s modulus were characterized using frequency-domain analyzes. In addition, an analytical approach was proposed based on the use of the Hanning window to capture the modal shape and damping information of a three-degree-of-freedom system by analyzing the vibration signals during their free vibration phases. Also, the successful application of the STFT was revealed in identifying the vibration features of the signals compared to the estimation performance of a validated Q-factor technique.

Dolce and Cardone [21] demonstrated the accurate performance of STFT in representing the spectral features of the signal responses of shape memory alloys (SMAs) simultaneously in both time and frequency domains. A damage

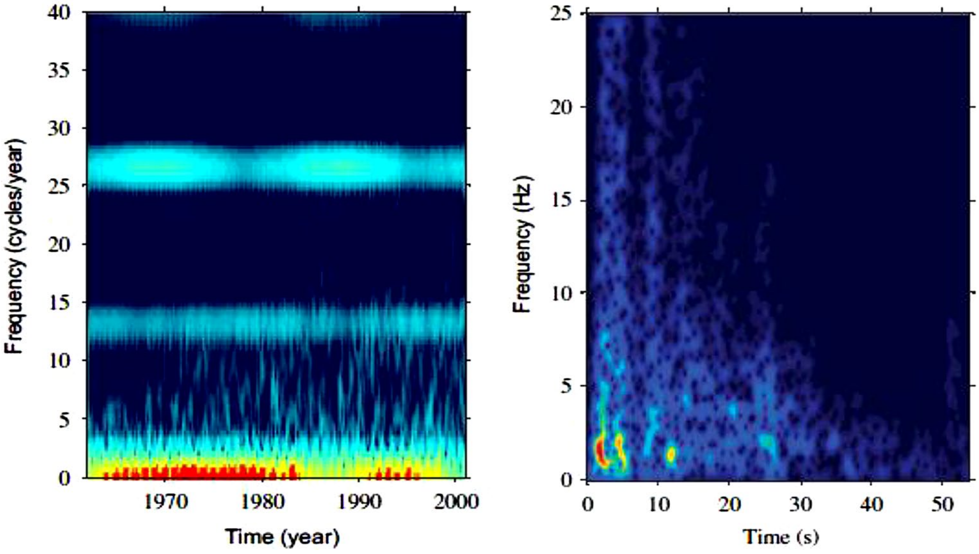


Fig. 1 (**a**) Time varying spectra of the acceleration record of El Centro (1940, N–S) and, (**b**) the daily length of day data of a 7-story RC framed building obtained by the STFT method [16]

index based on the averaged STFT spectrogram method was adopted by Cocconcelli et al. [22] for damage detection of direct-drive motors. The proposed damage index was calculated based the marginal integration in time series of the signal responses. The performance of the STFT in the implementation of a output-only damage identification method on multi-degree of freedom (MDOF) systems representing linear time invariant (LTI) and linear time variant (LTV) behaviors, was evaluated by Nagarajaiah and Basu [23] in comparison with the performances of empirical mode decomposition (EMD) wavelet techniques. It was found that the STFT can efficiently characterize the damage as well as the EMD and wavelet methods. The successful application of the STFT has been also reported in SHM of tuned mass dampers [24–29] and mechanical systems [18] as well as the capabilities if the EMD and Hilbert Transform (HT) techniques. Kim et al. [30] carried out a comparative study on the feature extraction performances of various time-frequency techniques including the FFT, STFT, Wigner–Ville Distribution (WVD), and Discrete Wavelet Transform (DWT) in damage detection of a spindle-typed rotor-bearing system. As shown in Fig. 2, the STFT methods can identify the time and frequency characteristics of the damage as well as the WVD and presents better performance compared to FFT. A time-frequency algorithm based on the application of the STFT was proposed by Fitzgerald et al. [31] for damage identification in the numerical model of the blade of a wind turbine by analyzing the rotations velocity and the stiffness features of the blade. The sensitivity of the proposed method was concluded to the existing of structural faults due to the stiffness changes and frequency changes varying in time distributions.

The capability of the STFT technique in the damage detection, localization, and classification of a laboratory-scale steel truss bridge model was demonstrated by Mousavi et al. [32]. As such, STFT was utilized to illustrate the change of frequency content when a series of damages accrued in a steel truss bridge model. As shown in Fig. 3, the magnitude of instantaneous frequency (IF) power enhances

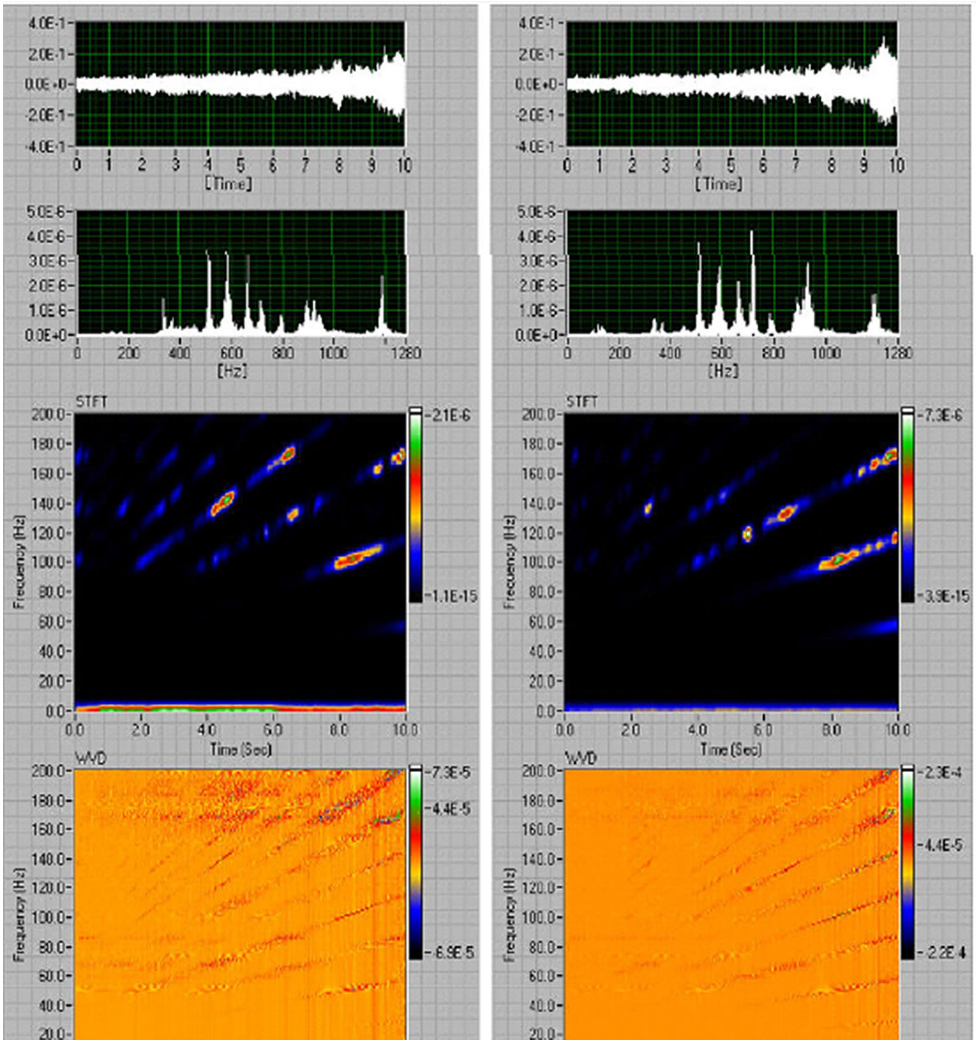


Fig. 2 Time signal, FFT, STFT, and WVD of normal and crack condition during acceleration [30]

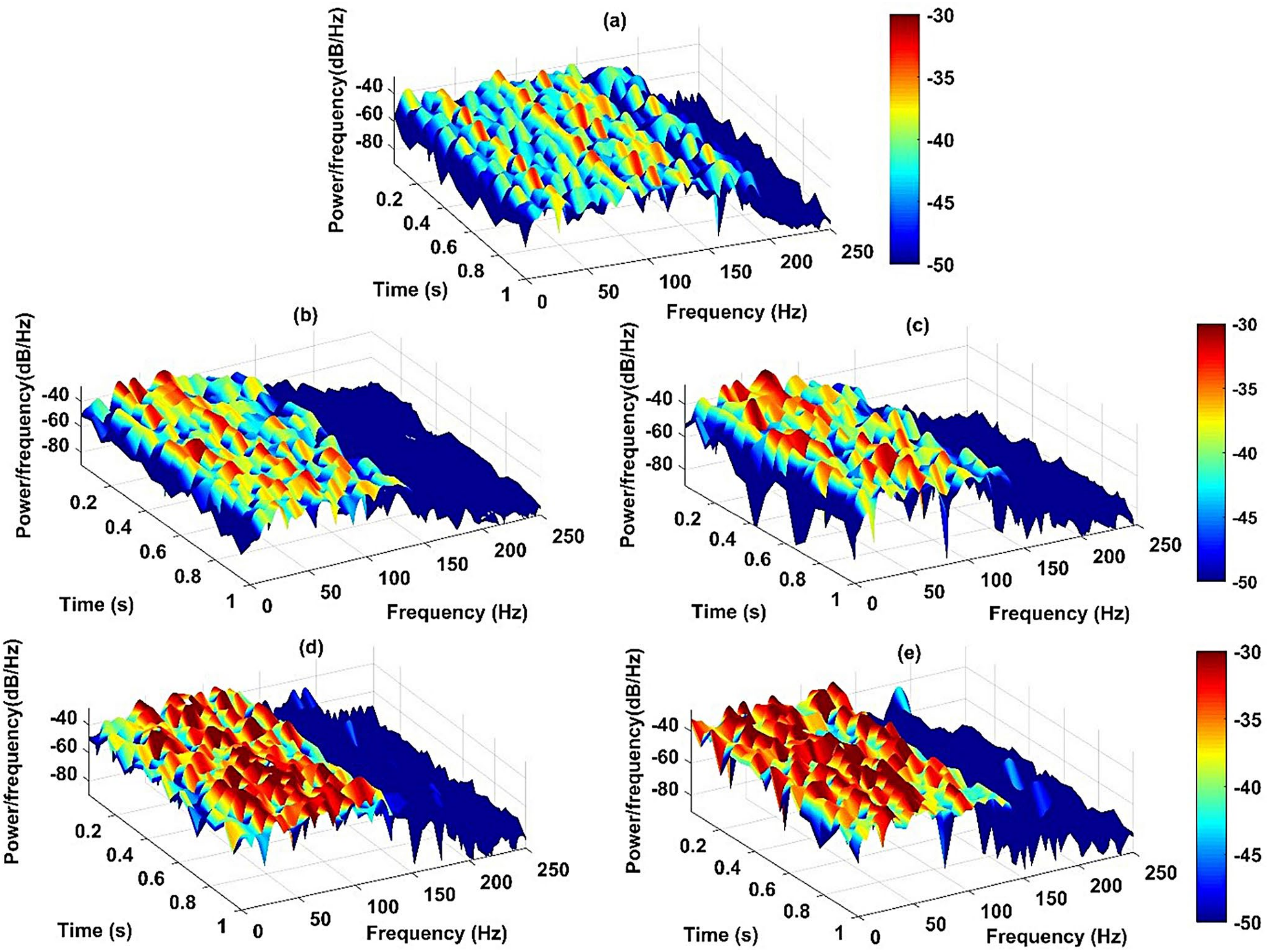


Fig. 3 Spectrograms of the IMFs of sensor-10 under five different states of the truss including; (**a**) healthy, (**b**) 20% damage, (**c**) 50% damage, (**d**) 80% damage, and (**e**) 100% damage [32]

in the low-frequency ranges compared to the healthy state as the damage severity increases.

3 Hilbert Huang Transform (HHT)

Frequency-based signal processing techniques have substantial drawbacks in deriving the time related features of the analyzed signal [33]. Also, these techniques cannot properly determine the information of higher frequency modes that basically represent the characteristics of the signal faults [34–36]. To solve these issues, several improved signal processing techniques such as wavelet transform (WT) [37–39], Hilbert-Huang transform (HHT) have been proposed in the recent years. HHT is a novel signal processing technique that was proposed by Huang et al. [40, 41] based on the combination of Hilbert transform (HT) and EMD techniques to analyze nonlinear and nonstationary signals. The procedure of EMD is based on the decomposition of signal data into a series of finite intrinsic mode functions (IMFs) as such it can efficiently capture the time-dependent instantaneous responses of the analyzed signal. The EMD has been widely used in the literature for the damage detection of civil engineering structures representing nonstationary and nonlinear responses in the real world [42–44, 45, 46]. However, there still exist substantial issues with the implementation of HHT for SHM of structures. To overcome the exiting drawbacks of the EMD such as mode mixing problem, ensemble empirical mode decomposition (EEMD), and complete ensemble empirical mode decomposition with adaptive noise (CEEMDAN) techniques were proposed as the improved HHT techniques that will review in the following sections. Table 1 presents a list of some indexed research works utilizing the HHT techniques on different analytical, numerical, experimental models of various types of structures with representations in time-frequency domains.

Table 1 Summary of using frequency-time domain signal processing techniques in damage detection of civil structures

Authors	Name of technique	Analyzed structures	Level of damage detection
Rezaei and Taheri [46]	EMD	Cantilevered steel beam (N, L)	Existence
Dong et al. [47]	EMD	The Imperial County Services Building (R)	Existence
Cheng-Zhong and Lian Xu-Wei [48]	EMD	Transmission tower (R)	Existence
Xu and Chen [49]	EMD	Three-story shear building (L)	Existence
Sarmadi et al. [50]	EEMD	Four-story steel frame of a IASC-ASCE model (L)	Existence and location
Entezami and Shariatmadar [51]	EEMD	Four-story steel structure (L)	Existence and location
Mousavi et al. [32]	CEEMDAN	Steel truss bridge (L)	Existence, severity, and location
Fakih et al. [52]	CEEMDAN	Friction stir welded joints (N, L)	Existence and severity

Note: N - numerical, L - Laboratory, R - real-life

3.1 Empirical Mode Decomposition (EMD)

The basic procedure of EMD is adopting a sifting process to decompose the measured signals into a set of IMFs through and consequently extracting the feature information in time and frequency domains. In this technique, the characteristics of at least two extrema in terms of their magnitudes and time intervals are required for decomposing the raw signals. The main advantage of EMD compared to frequency-based techniques is that this technique can efficiently analyze the nonlinear and nonstationary signals and represent the information of the extracted features in both time and frequency domains with relatively high resolution. There exist many research works in the literature that have been reported the application of the EMD in analyzing the vibration signals recorded from the civil engineering structures. The capability of the EMD technique was proved by Pines and Salvino [53] in damage detection of experimental and analytical models of one-dimensional (1D) structures. Rezaei and Taheri [46] proposed a novel damage indicator based on the energy feature of the vibration signals extracted by EMD to detect the size, severity and location of notch damages in the numerical model of a cantilevered steel beam. The HHT based on EMD method was employed for SHM of the Guangzhou New TV Tower (GNTVT) as shown in Fig. 4 during the construction and service phases of the tower when subjected to typhoons and earthquakes. Once acquiring the signal data from different sections the tower as shown in Fig. 4, the HHT was applied to signal modes decomposed by EMD for identifying the frequency-based features such as the natural frequencies and damping ratios, and time-related parameters including the instantaneous frequencies and energy features represented in time-frequency domains compared to the results from wavelet transform techniques.

A hybrid damage detection approach from the combinations of the EMD and a time-series based feature extraction technique named vector autoregressive moving average

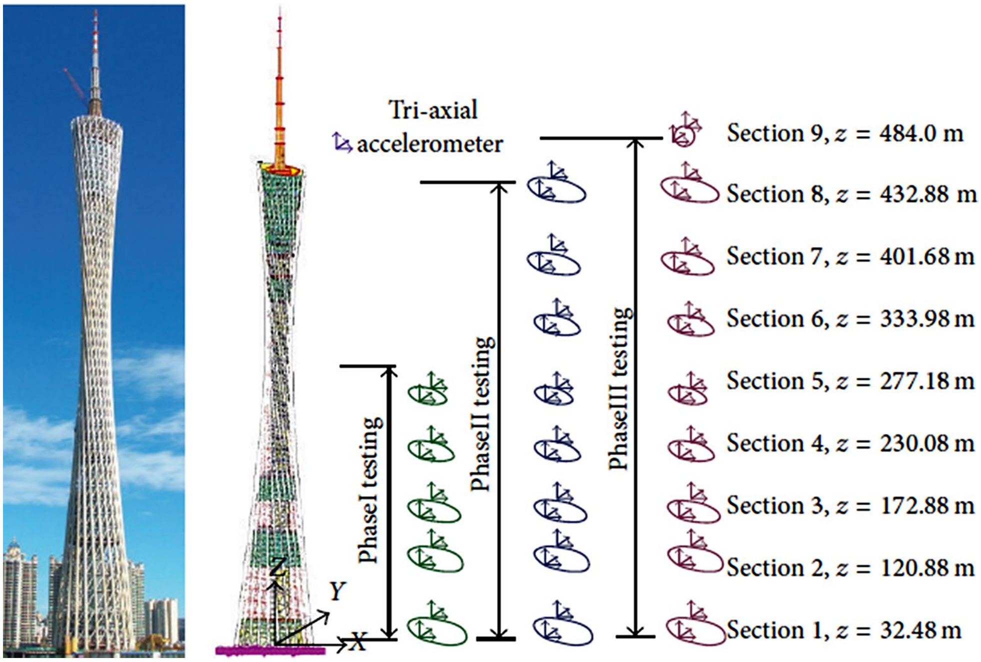


Fig. 4 Guangzhou New TV Tower [46]

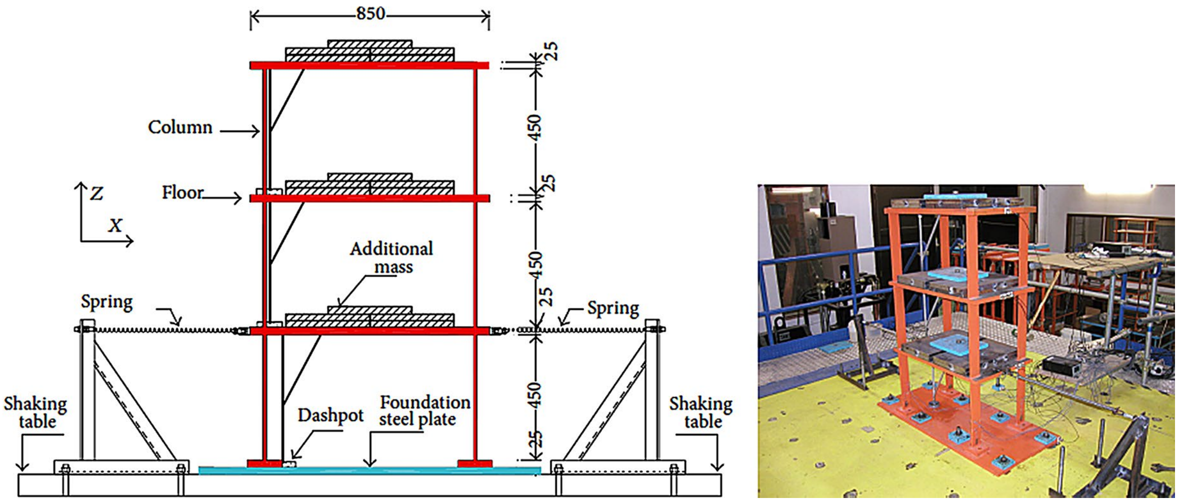


Fig. 5 Configuration of the building model (unit: mm) [46]

Fig. 6 Figures 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16 and 17 A photograph of the NYR steel truss bridge [56]

(VARMA) model was proposed by Dong et al. [47] for SHM of the Imperial County Services Building and the Van Nuys Hotel. The procedure of the proposed method was based on the detection of sudden energy variations in time-frequency distributions especially when occurring at high ranges of the frequency responses. The combination EMD-HHT techniques was used by Cheng-Zhong and Lian Xu-Wei [48] for damage identification of a transmission tower through characterizing the shape factor feature of the analyzed signals. Xu and Chen [46, 54] employed the EMD for the damage detection of a laboratory model of a three-story shear building under vibration excitations applied through a shake table as shown in Fig. 5. An application of an adaptive HHT method for identifying the modal responses of a composite beam was reported by Bao et al. [55]. It the proposed method, the HHT was improved by using an autocorrelation algorithm combined with a band-pass filter for the purpose of noise reduction in the measured signals. The EMD was used by Rezaei and Taheri [49] for damage detection and classification in the numerical and experimental models of a steel beam. In this study, the energy feature of the first IMF obtained from the decomposition process by EMD was considered as the damage indicator.

As a field application of the EMD in the real world, He et al. [56] used the combination of the EMD and the random decrement technique (RDT) for identifying the modal characteristics of a railway bridge in China as shown in Fig. 6. In addition, a FE (finite element)-based comparative study was carried out to evaluate the capability of the EMD-RDT method compared to the results from performing peak-picking approach. The superiority of the EMD-based technique was concluded in modal identification the studied bridge. An application of EMD-based HHT was also reported by Bao et al. [55] for structural damage identification, and detecting the damage location and its severity when subjected to ambient excitations.

Pavlopoulou et al. [57] conducted the SHM of an aluminum panel and fibre-epoxy composite laminates through the analysis of ultrasonic waves guided on these components using an EMD-based HHT technique. As another application of the EMD-based HHT method, Ghazali et al. [58] employed this technique for the damage detection in experimental and analytical models of a pipeline system. Esmaeel and Taheri [59] demonstrated the successful performance of a damage identification approach based on the application of EMD on the vibration signal data of a high-rise building structure. Also, the sensitivity of the proposed method to the damage severity and its dimensions was revealed. Alvanitopoulos et al. [60] also concluded the capability of the EMD-based HHT technique in identifying and characterizing the structural damage in RC framed structures through the analysis of the extracted signal features including peak and average values of the signal amplitude parameter. An efficient performance of a damage index based on the instantaneous frequency feature extracted by the EMD-based HHT method from the vibration responses of soil-quay wall systems, was concluded by Wei et al. [61] in detecting the seismic damages in these systems. In addition, this damage index was successful in identifying the incidence of the liquefaction and the time-dependent characteristics of the soil. The combination of EMD and RDT techniques was employed by Shi et al. [62] for characterizing the modal parameters of the Shanghai World Financial Center structure including the natural frequencies and damping ratio parameters when exposed to different excitations. Although the combined EMD-RDT technique accurately could estimate the natural frequencies of the structure, it was failed in identifying the damping ratios when the structure was exposed to ambient dynamic excitations. A combination of wavelet packet transform (WPT) and EMD techniques was used by Garcia-Perez et al. [63] for damage detection, localization and classification of its severity in a steel truss by defining an energy-based damage index. This hybrid method was effectively able to detect the presence and location of the fault due to various factors such as the loosened bolt at the joint connections, cross-sectional stiffness reduction, and corrosion.

Chiou et al. [64] introduced a new damaged indicator defined based the variations of the damping ratio feature of the vibration responses analyzed by the EMD-based HHT technique for damage identification of various benchmark models when exposed to different earthquake excitations. As an improvement on the traditional acoustic emission (AE) techniques, Lin and Chu [65] used the damage indices defined based on the energy and instantaneous frequency features extracted from the acoustic emission data in characterizing the damage at the joint connections of a steel offshore structure under tensile stresses. Similarly, an improved AE techniques by using EMD-based HHT was employed by Hamdi et al. [66] for damage identification of composite structures through a series of bending tests. The capability of this technique in the analysis of the nonstationary AE signals was concluded. The validation of the EMD-based HHT method was also examined by Lin et al. [67] in analyzing the impact-echo signals with high noise for damage detection of concrete components. Yadav et al. [68] used the EMD for extracting the signal features of the ultrasonic wave data obtained from a steel channel under moving loads to characterize the damage presence in this structure. A damage detection based on the application of EMD on the acceleration responses of a beam member was utilized by Meredith et al. [69]. The capability of this method in classifying even minor cracks with a severity of 10% under moving loads, was concluded. Roveri and Carcaterra [70] also revealed the efficiency of the EMD-based HHT technique in damage detecting and localization of bridges using the the analysis of signal data measured from only a single point under moving traffic loads. Also, Yu and Ren [71] concluded an accurate performance of EMD in identifying the modal characteristics of Xining Beichuan Arch Bridge as shown in Fig. 7.

Fig. 7 Xining Beichuan Arch Bridge [71]

The performance of EMD-based HHT in analyzing the nonlinear and nonstationary buffeting responses of a long-span bridge was evaluated by Ma et al. [72]. The EMD technique captured more accurate results in the time-frequency domains compared to FFT in identifying the frequency spectrum of the responses. A combination of EMD and spectral analysis was used by Chen et al. [73] for SHM of the Tsing Ma Suspension Bridge by measuring the strain, temperature, displacement, and acceleration responses data. The proposed hybrid technique was efficiently capable to capture the static and dynamic features of the measured noisy signal responses.

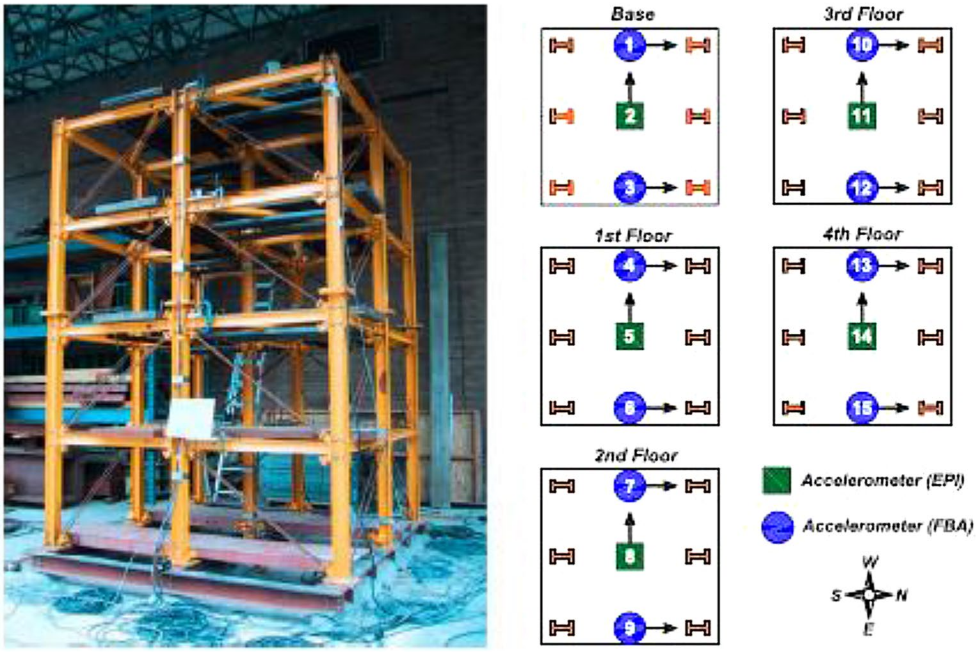
Zhang et al. [74] employed the EMD for analysis of the vibration responses a bridge system under wind excitations to identify the modal parameters including the instantaneous frequencies and damping ratios. The EMD could successfully detect the structural faults through realizing the behavioral changes in the modal characteristics. A hybrid damage identification technique from a combination of EMD and wavelet method was proposed by Yi et al. [75] to recognize the dynamic features of the wind responses of a high-rise building under typhoons. Despite capability of the EMD in capturing the vital dynamic and time-dependent features of signal, there exist a considerable mode mixing drawback associated with the performance of the EMD in analyzing signals having very close or same frequencies [76].

3.2 Ensemble Empirical Mode Decomposition (EEMD)

To overcome the mode mixing problem of EMD, the EEMD technique was introduced by Wu and Huang [76] in which a white Gaussian noise is separately added to each IMF of analyzed signal with an identical standard deviation. The application of the EEMD has been widely reported in the literature for the purpose of solving the mode mixing issue of the EMD. A combination of EEMD and RDT method was used by Liu et al. [77] in which the statistical autoregressive vector (ARV) was employed as the feature extraction tool for characterizing the modal parameters of the Xing Nan Bridge under ambient dynamic excitations. It was found that although the EEMD could not only efficiently identify the modal features of signals whiout any mode mixing problem, it requires more computational costs compared to the use of EMD because of utilizing the added white noise in obtaining the IMFs [78]. By comparing the performances of the EMD and EEMD techniques in analyzing the seismic signals by Wang et al. [79], the superiority of the EEMD in the decomposition of the IMFs without any mode mixing problem and better presentation of the results in time-frequency domains was concluded. Besides, Lin [80] found that a combined use of EMD and EEMD have some advantages compared to the sole application of the EMD in the analysis of the responses of a bridge. A hybrid signal processing technique based on the combined EEMD and the multiple signal classification approach (MUSIC) technique was proposed by Martinez [81] to characterize the modal characteristics of a truss bridge model. The superior performance of the proposed method in the presentation of the signal features time-frequency domains was concluded compared to the performances of traditional techniques such as DWT and FFT methods. Amiri and Darvishan [82] carried out a comparative study on the performances of the EEMD and EMD techniques by adopting density-based clustering technique in evaluating the acceleration signals of a steel frame based on the analysis of the frequency and amplitude features. An energy-based damage identifier was proposed by Sarmadi et al. [50] was concluded by using EEMD as the feature extraction method combined with Pearson correlation function for damage detection and localization in an IASC-ASCE structure model when subjected to ambient vibrations as shown in Fig. 8. The IASC-ASCE structure model was also used by Entezami and Shariatmadar [51] to evaluate the performance a new hybrid damage identification method from a combination of EEMD and auto regression model with exogenouinput (ARARX), and correlation-based dynamic time warping techniques. The capability the proposed method was found in detecting the damage presence and its location.

3.3 Complete Ensemble Empirical Mode Decomposition with Adaptive Noise (CEEMDAN)

Despite aforementioned advantages of the EEMD over EMD, there exist two major drawbacks associated with the performance of EEMD due to adding white Gaussian noise to the signal leading to difficulties in obtaining the average of IMFs and existing residual noise in IMFs. To solve this issue, the complete ensemble empirical mode decomposition with adaptive noise (CEEMDAN) technique was proposed by Torres et al. [78] in which a particular noise is added to IMFs at each stage resulting in unique residues for each IMF. Additionally, CEEMDAN has a proper spectral separation which considerably reduces the time of decomposition process. The three aforementioned EMD-based



(a)

(b)

Fig. 8 (**a**) A four-story steel structure of studied as the IASC-ASCE structural health monitoring benchmark problem by Sarmadi et al. [50], (**b**) Sensor numbers and locations techniques have been widely used in mechanical [83–86], geological, seismic signals [87] and electrocardiogram (ECG) [78] application. However, CEEMDAN has been rarely used for SHM of civil engineering structures. The application of CEEMDAN in analyzing the seismic signals was reported by Han and Baan [88] to improve the resolution of the results in time and frequency domains and to solve the mode mixing issue of EMD. The performance of CEEMDAN in analyzing the acceleration responses of a steel-truss bridge model as shown in Fig. 9 under white noise excitations was experimentally evaluated by Mousavi et al. [89] using four signal features extracted from the IMFs including the energy, instantaneous amplitude, unwrapped phase, and instantaneous frequency. In addition, several damage indices based on the hybrid applications of two statistical time-history features, including kurtosis and entropy features with the energy and instantaneous amplitude features were proposed. The superiority of CEEMDAN in detecting the presence, and location of damage and quantifying its severity was concluded compared to EMD and EEMD. Afterwards, Mousavi et al. [32] utilized CEEMDAN in combination with an artificial neural network for structural damage localization and quantification of a steel-truss bridge model experimentally subjected to white noise excitations as shown in Fig. 9. Experimental results demonstrated the robustness and efficiency of using CEEMDAN in damage detection. In line with these studies, a combination of CEEMDAN and MUSIC technique named CEEMDAN-MUSIC was proposed by Mousavi et al. [90]. The results demonstrated the advantages of the proposed techniques in damage detection and localization compared to pure CEEMDAN.

Xiao et al. [91] introduced a SHM model by employing CEEMDAN and Hilbert transform to extract the spectrum signature of a bridge vibration under a vehicle moving load. Li et al. [92] introduced an energy based feature extraction methodology using CEEMDAN for ship-radiated noise (S-RN). Lv et al. [93] applied CEEMDAN improved multivariate multiscale sample entropy (MMSE) to detect faults in a rolling bearing system and the capability of the proposed methodology was concluded. The capability of a fault diagnosis approach from a combined application of CEEMDAN and Adaptive Neuro-fuzzy Inference System (ANFIS) was reported by Kuai et al. [94]. A damage index based on Improved CEEMDAN introduced by Fakih et al. [52] to detect the presence and assess the severity of damage resulting from the flaws in friction stir welded joints. Experimental and finite element analysis reveal high sensitivity of the proposed method.

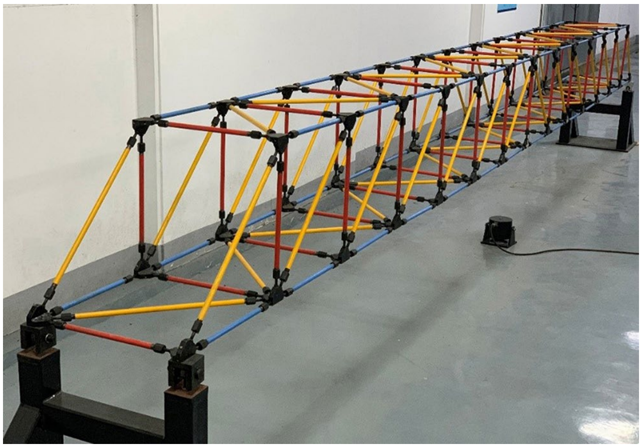


Fig. 9 A perspective view of the truss in the laboratory of Qingdao University of Technology by Mousavi et al. [32, 89–90]

4 Wavelet Transform (WT)

Despite common applications of FFT in analyzing stationary signals that represent constant characteristics without nonlinearity, it is not efficiently capable to process nonlinear and non-stationary signals. Due to the advantages of wavelet transform (WT) techniques in analyzing the nonlinear and non-stationary signals in time-frequency domains through adopting specific filters, have motivated researchers to widely use of these methods for SHM of real-world structures in the recent years. The WT is also able to improve the drawbacks of the STFT in terms of the time-frequency representation of data. That is, the spectral characteristics of analyzed time series can be presented with higher resolutions by WT by performing a multi-resolution analysis to identify the time-dependent variations in time-series. The procedure of this resolution analysis by WT is based on the use of different-size wavelets adapted with the size of the target signal features. The use of WT technique is not only limited to analyze the signals of civil engineering structures but also many research works has reported the expensive application of WT-based techniques in improved forms such as continuous wavelet transform (CWT), discrete wavelet transform (DWT), wavelet multi-resolution analysis (WMRA), wavelet packet transform (WPT), synchrosqueezed wavelet transforms, empirical wavelet transform (EWT), etc. for SHM of various engineering systems [20, 95, 96].

4.1 Continuous Wavelet Transform (CWT)

The continuous wavelet transform (CWT) is a formal tool that provides an improved representation of a signal in time-frequency domains by adopting the wavelets with different scales of parameters that continuously vary depends on the size of the target features. The signal faults commonly are detected using CWT based on the analysis, scaling, and

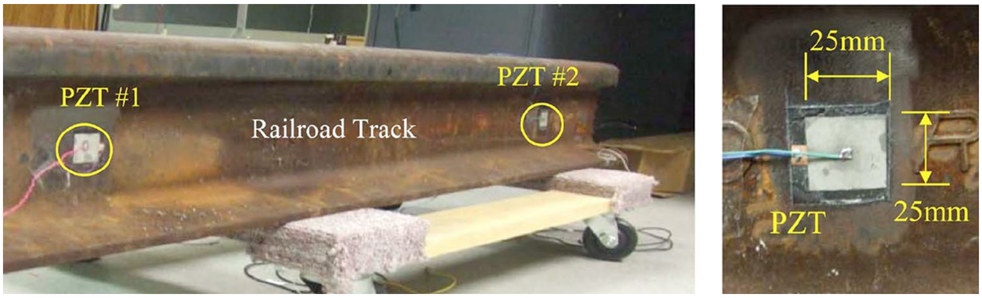


Fig. 10 Test specimen and built-in PZT patch [100]

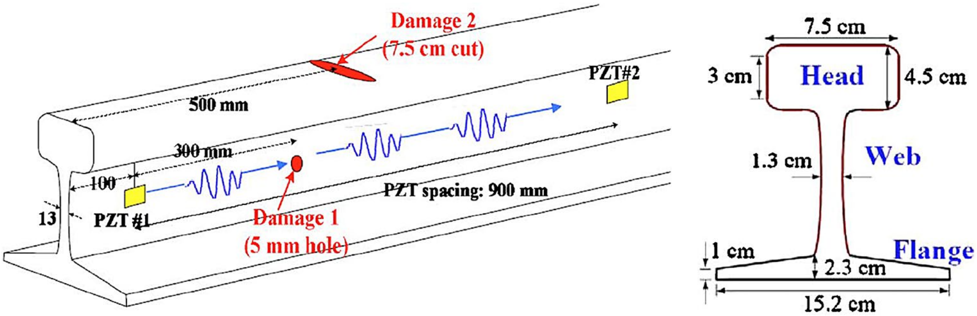


Fig. 11 Damage descriptions on railroad Sect. [100]

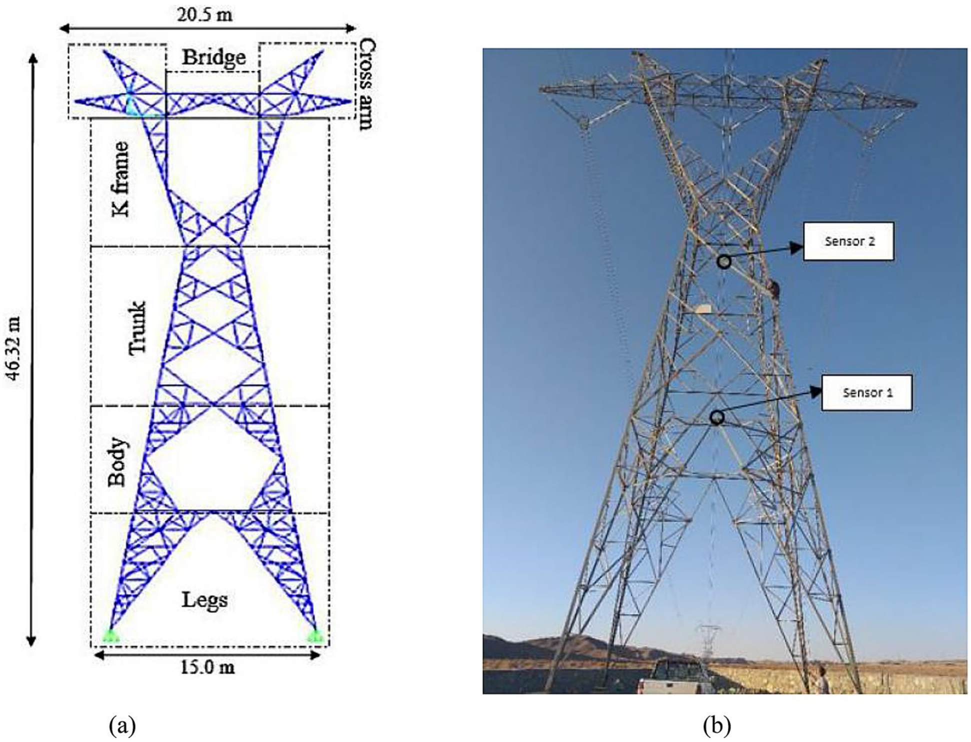
transforming the basic functions on a mother wavelet. Several previous studies have reported the use of CWT for the damage detection of different structural and mechanical systems.

Okafor and Dutta [97] employed CWT for damage identification in cantilever beams by determining the continuous wavelet coefficients through a Daubechies mother wavelet. The damage states were applied to the finite element (FE) models of the beams by reducing their stiffness. The CWT efficiently detected the damage location though characterizing the spikes in the signal behaviors. The Morlet mother wavelet was used in the CWT by Yoon et al. [98] for identifying the corrosion damage and its severity in RC beams through the analysis of Acoustic Emission (AE) signals. The CWT technique could successfully categorized the damage mechanisms and failure behaviors of the beams including localized minor cracks, flexural and shear damages by specifying their relevant frequency changes. The CWT based on processing the variations of ridge patterns was employed by Melhem and Kim [99] for detecting the presence of fatigue damage in RC slabs and beams with simple supports. As a result, it was found the number of clear ridges increased with increasing the damage severity and growing the cracks, especially in large-scale (with low-frequency responses) RC structures. In addition, the superiority of the CWT in analyzing the nonstationary signals was concluded in comparison with FFT. The validity of a hybrid damaged detection approach from the combination of the CWT by adopting the Morlet mother function and a two-step support vector machine (SVM) classifier was demonstrated by Park et al. [100] for detecting and classifying the damages in railroad tracks as shown in Figs. 10 and 11. The seismic responses of RC columns and a four-story steel frame was analyzed by Noh et al. [101] by using the CWT based on the Morlet mother wavelet for the damage detection. In this technique, the CWT adopted three damage sensitive features (DSFs) to characterize the energy variations of the wavelets in proportion to changes in damage patterns of the structure. The reliability of the employed technique was approved by correlating the results compared to the classification of damage mechanisms using the drifts between the stories. Su et al. [102] proposed a hybrid damage identification approach from the combination of the CWT based on Daubechies mother wavelets and an efficient time varying autoregressive with exogenous input (TVARX) to determine the instantaneous modal parameters of a linear time varying structure under an earthquake excitation. The proposed method was efficiently able to detect the location of the structural damage without any need for a reference data. Li et al. [103] demonstrated that the application of a Butterworth filtering in combination with CWT adopting a Morlet mother wavelet could adequately detect the structural faults and crack patterns in a three span cable-stayed bridge by removing the environmental effects.

A hybrid application of CWT and HT techniques was used by Gaviria and Montejo [104] for identifying the signal features and reconstruction of the analyzed signals of an RC structure under seismic excitations. The capability of the proposed method in obtaining the modal parameters including the natural frequencies and the damping ratio was concluded as well as identifying the structural characteristics including the mass and stiffness matrices. In addition, the capability of this technique was validated in efficiently detecting the presence, and location of the damage, and in classifying its severity. Gholizad and Safari [105] identified the structural damages in space structures through the analysis of the variations occurred in the mode shape features of the signals by employing the CWT technique in which the Mexican hat mother wavelet was adopted. The existence and location of damages on the tubular elements and joints were adequately detected using the CWT method. With the intention of identifying the damage presence and location in a steel beam, Shahsavari et al. [106] proposed a CWT-based statistical analysis in which a Symlet wavelet performed in combination likelihood-based statistical methods. According to this method, first, the signal modes extracted by application of the CWT were analyzed to detect the damage. Then, the analyzed signal modes were evaluated using a likelihood ratio test to detect the location of the damage. The difficulties associated with probabilistic analyses in computing unbiased distribution of uncertainties was improved by utilizing a CWT-based non-probabilistic technique by Abdulkareem et al. [107] as a damage detection approach for a steel plate. The damage detection process of the method was based on a damage indicator defined by determination of the upper and lower bounds of the wavelet coefficients. The CWT by adopting a Mexican hat mother wavelet was also utilized by Wang et al. [108] for damage identification and characterization in a metro tunnel. Also, a damage index was defined based on the residual force vectors of the damaged structure compared to those of the healthy state of the tunnel. The capability of this method was concluded detecting the damage location in the tunnel and classifying its severity. A hybrid damage detection framework by using kernel function based on the combination of SVM and CWT with a Morlet mother wavelet, HHT, Teager-Huang Transform (THT) was proposed by Pan et al. [109] for SHM of a cable-stayed bridge. Also, a parametric study was carried based with variations of the damage severity and its location. The superior performance of CWT in analyzing noisy signals was concluded compared to HHT and THT. As a real-world application, Karami-Mohammadi et al. [110] used the CWT for damage detection and localization in power transmission towers as shown in Fig. 12 through determining the characteristics of their vibration responses. It was demonstrated that CWT was able to properly identify the structural faults by characterizing the modal parameters of the vibration responses such as the curvature of the mode shapes.

4.2 Discrete Wavelet Transform (DWT)

The discrete wavelet transform (DWT) is known as another popular WT technique in signal processing which is performed by discretization of parameters in CWT. The main advantages of CWT are associated with the considerable capability of this technique in processing different scales and segments of signals, and redundancy of CWT as such it represents significant overlap between wavelets at each scale and between scales. However, the application of CWT requires high computational cost since it represents a high-redundant data analysis approach. In contrast, DWT



(a)

(b)

Fig. 12 (**a**) Geometry and dimensions and (**b**) experimental test of the case study tower [110] represents a non-redundant analysis requiring lower computational time due to the use of orthogonal functions in the decomposition signals. As much as extensive application of CWT for SHM of different systems, there exist many research works in the literature reporting the widely use of DWT as a popular data processing technique with time-frequency representations. Hou et al. [111] employed CWT and DWT techniques by adopting the Daubechies mother wavelet for damage diagnosis in a simplified SDOF (single degree of freedom) system. The capability of the both WT-based techniques was demonstrated in detecting the existence and location of the damage through identifying the characteristics of the spikes observed in the wavelet responses of the signals. Hera and Hou [112] performed DWT for detecting the damage in a four-story steel frame structure of ASCE benchmark model under wind load excitations. The DWT could efficiently identify the structural damages in the brace elements through characterizing the response spikes appeared in the wavelets. Besides, the damage location was recognized using the distribution patterns of the spikes. Ovanesova and Sua´rez [113] successfully recognized the crack patterns, the damage severity, and its location in an RC beam using the application of DWT with different mother wavelet functions on the beam responses and consequently identifying the wavelet coefficients. The variations of the wavelet coefficients were identified through observing discontinuity behavioral trend and detecting any sudden changes in the resolution of the scalograms. Hoseini Vaez and Tabaei Aghaei [114] employed DWT for damage detect through observing spikes in the wavelet plots of the analyzed signal.

4.3 Wavelet Multi-Resolution Analysis (WMRA)

The basic concept of WMRA is to perform DWT by adopting different filters. This technique is able to present different resolution data of an analyzed original signal including data with coarse and fine resolutions that contain information associate with low- and high frequency signal modes, respectively. The application of WMRA in combination with DWT technique as a time-frequency technique has been reported in signal processing and SHM of various structural and mechanical systems by several previous studies [109, 115–120].

A damage detection approach based on the use of coarse resolution analysis of WMRA to obtain low-frequency information of data from a series of beam members was employed by Feng et al. [115]. In this method, first, the strain data of the beams was analyzed using DWT and the wavelet coefficients of the decomposed signal were obtained. Thereafter, the fault features were identified through additional transformations were implemented on the captured WT coefficients using multiresolution analysis. The capability of the DWT-WMRA in detecting the location of cracks in the beams was concluded even in a noisy environment. As another hybrid signal processing technique utilizing WMRA, the successful performance of a hybrid damage identification approach from the combination of WMRA and ANN (artificial neural network) proposed by Lucero and Taha et al. [116] was demonstrated for of an RC bridge. Furthermore, a combination of WMRA with HT technique was employed by Djebala et al. [117] for fault diagnosis in a gear system. In this method, the signal modes decomposed using HT were further analyzed by WMRA to identify high-frequency fault features through high-resolution information. Datta et al. [118] also evaluated the performance of a hybrid technique from the combined applications of a WMRA and a neural network for diagnosing damages in industrial robots. The validity of the utilized approach was demonstrated by using the experimental data obtained from an industrial robot manipulator. As a practical study on the application of WMRA on structural members, Zhang et al. [119] analyzed the acceleration responses of a laboratory-scale model of a RC beam as shown in Fig. 13 and the capability of a hybrid algorithm adopting WMRA in combination a wavelet damage function was concluded.

4.4 Wavelet Packet Transform (WPT)

Similar to the performance of WMRA, wavelet packet transform (WPT) which represents an extension form of WT, analyzes signals by classifying their components to high- and low-frequency modes. WPT is also able to completely decompose signals so that obtain signal time-frequency features representing both stationary and non-stationary characteristics [120].

This analysis method has advantages over WMRA in terms of providing a more detained and flexible analysis procedure for signals in which wavelet packets perform based on the linear combinations of wavelet functions. The application of WPT in damage detection and SHM of different systems has been extensively reported in the literature [121–127]. A hybrid application of WPT and the neural network techniques was used by Sun and Chang [121] for damage detection in a three-span continuous beam when subjected to impact loads. According to this method, the wavelet components obtained from the decomposition of the signals by WPT for different states of the beam were used as the inputs of the neural network. The proposed method was efficiently able to detect the presence, location and severity of the damage. Yam et al. [122] used the energy-based damaged detection approach in which the energy feature of the vibration responses was obtained by using WPT. The capability of WPT in identifying the damage in steel beams was

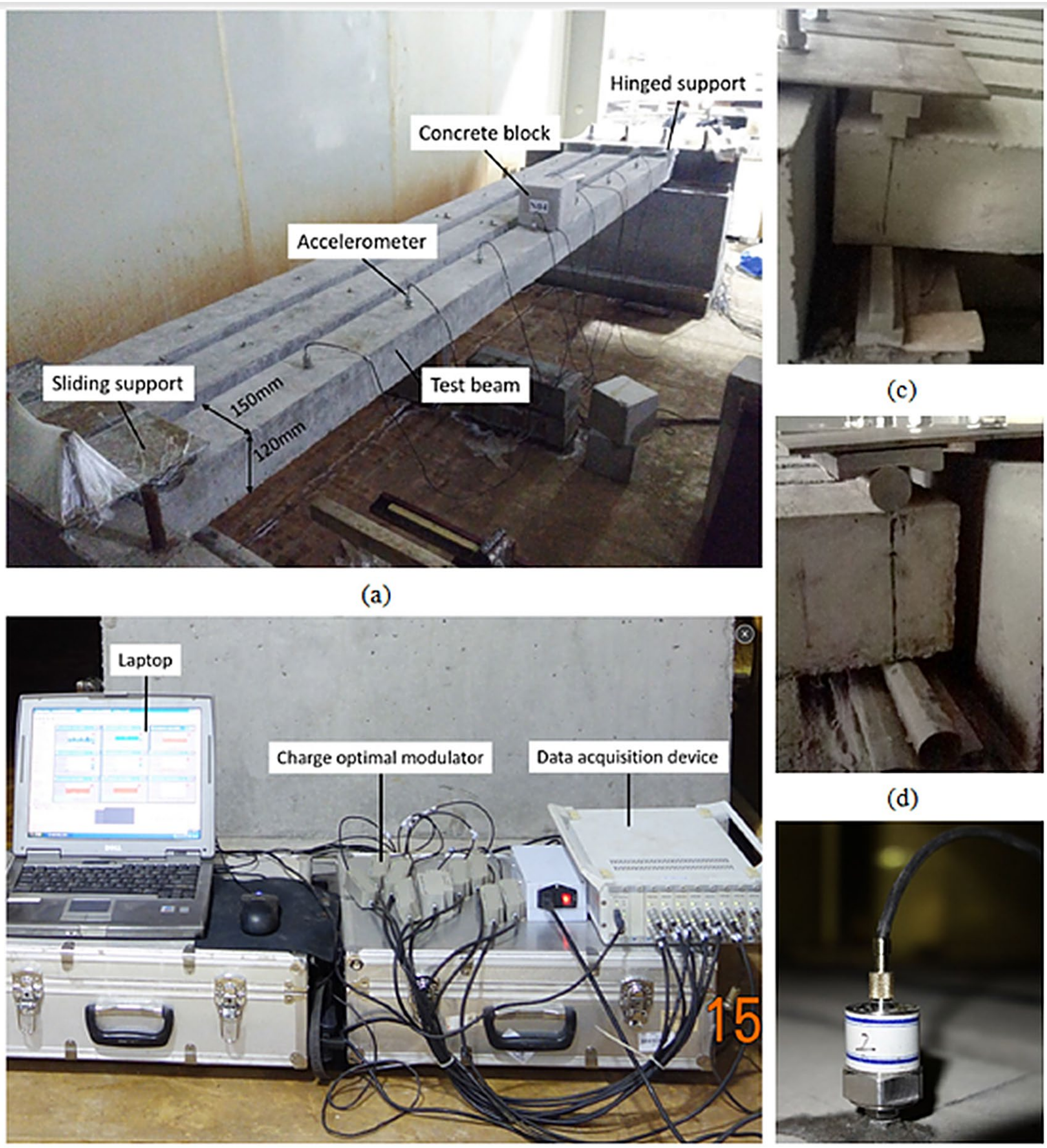


Fig. 13 Experimental layout: (**a**) overview, (**b**) data acquisition instruments, (**c**) hinged support, (**d**) sliding support, and (**e**) piezoelectric accelerometer [119]

also presented by Han et al. [123] by using a novel damage indicator based on the wavelet packet rate. The existence of structural faults in the shear connectors of a reduced-scale model of a steel bridge was evaluated by Ren et al. [124] under impact loads based on the variations in the behavioral trend of the wavelet packet energy feature of the response signals obtained using WPT technique. It was found that the energy-based WPT was successful not only in detecting the presence of the damage but also efficiently recognized the location of the damaged connectors. The energy rate of the analyzed signals by WPT was also considered by Asgarian et al. [125] as a damage indicator for an offshore platform. The successful performance of WPT in processing the vibration responses of a one-story RC frame was demonstrated by Chan et al. [126] under different seismic excitations. Nie et al. [127] used a hybrid damage identification approach based on a combination of WPT and principal component analysis (PCA) for a laboratory-scaled steel beam as illustrated in Fig. 14. The accuracy of the proposed hybrid method in detecting the location of the damage was concluded.

4.5 Synchrosqueezed Wavelet Transforms (SWT)

Synchrosqueezed wavelet transforms (SWT) are new WT-based techniques proposed by Daubechies et al. [128] that

Fig. 14 Experimental model of a laboratory-scaled steel beam [127]

can efficiently analyze the nonlinear and non-stationary signal with high signal-to-ratio (SNR). The procedure of SWT is based on the relocating the frequency-based information of the CWT coefficients to capture time-frequency components with higher resolutions. In this method, first, the reconstruction of analyzed signals are performed by accumulating the features of signal components followed by determining the main frequencies of signals in time-frequency domains. Accordingly, the SWT can adequately detect the main frequencies of noisy signals. Wen et al. [129] proposed a combined application of SWT and SVM for fault diagnosis in a bearing system. In this method, first, the acceleration signals were decomposed into a series of IMFs using SWT. Then, the capability of the proposed hybrid SWT-SVM model in classifying the damage states of the bearing based on the energy feature of IMFs was concluded. A combination of SWT and the random decrement technique (RDT) was employed by Perez-Ramirez et al. [130] to identify the modal parameters of a 40-story steel frame as shown in Fig. 15 including the natural frequencies and damping ratio.

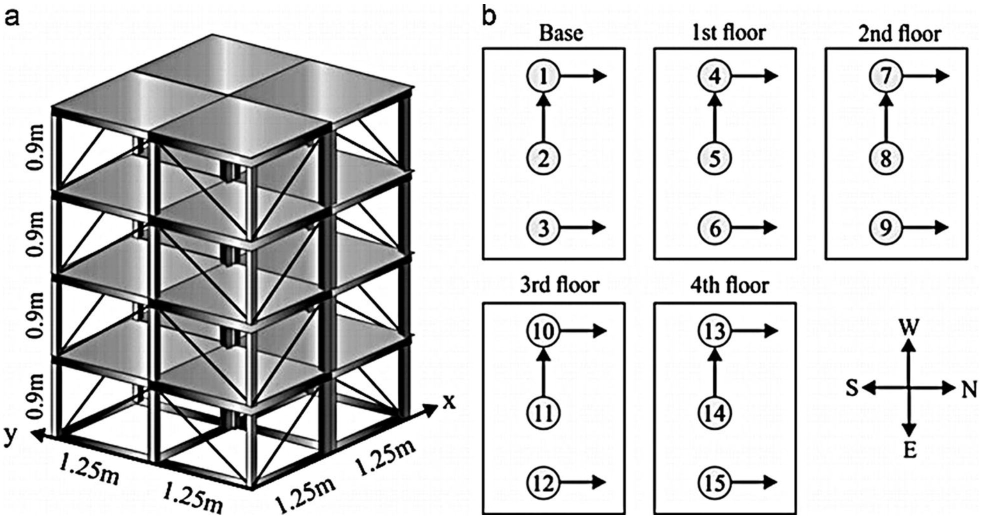
A novel damage detection approach based on the combined actions of SWT and fractal dimension (FD) analysis named SWT-FD was proposed by Amezquita-Sanchez and Adeli [131] for damage detection, and localization in a reduced-scale model of a 38-story concrete building structure under seismic excitations. The damage detection process of this model was based on application of different algorithms of the FD technique on the measured vibration responses of the structure to identify the signal features followed by a denoising step of signals by SWT.

The SWT technique was introduced as an optimal signal processing technique by Wang et al. [132] in term of consuming lower computational time in localizing the damage in a steel bar and a concrete structure. It was found that SWT can reduce the computational time without any considerable reduction in its performance accuracy. Li et al. [133] employed a combination of SWT and a multi-branch convolutional neural network on the acoustic emission waves of a rail track for detecting cracks in a railroad track and demonstrated its capability in detecting the crack existing not only on the surface of the track as shown in Fig. 16, but also those generated inside the track. Su et al. [134] revealed the high efficiency of a new hybrid damage detection approach based on the use of SWT the application of SWT in combination with stack autoencoder algorithm for detecting the location of damage in composite plates when subjected to strong noise background.

4.6 Empirical Wavelet Transform (EWT)

The empirical wavelet transform (EWT) technique was introduced by Gilles [135] to solve the drawbacks of EMD such as low frequency resolution leading to inability of EMD in separating the signal components in which the

Fig. 15 (**a**) Four-story test steel frame and (**b**) Location of the accelerometers on the structure [130]



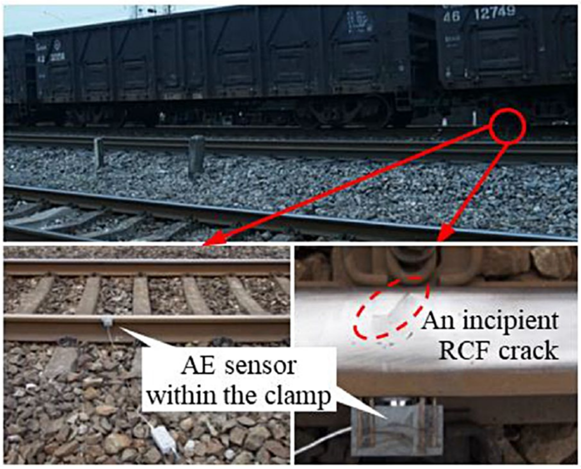


Fig. 16 Experimental setup of field tests of a rail track [134]

ratio of low frequency of the signal to its high frequency is greater than 0.75. This advantage enables the EWT to efficiently analyze the nonlinear signals with reserving the original information of the analyzed signal and represent the results in time-frequency domains with high-resolution. The procedure of EWT is based on the decomposition the original signal into a series of mode component by a suitable wavelet filter bank built using Fourier spectrum. Due to the validate capability of the EWT in processing the non-linear and non-stationary signals, the use of this technique have been extensively reported in the literature for damage detection in various structural and mechanical systems based on the analysis of the signal components captured through the application of the Fourier spectrum of signals. Despite the aforementioned advantages of the EWT in the analysis of nonlinear signals, it has a serious limitation in processing noisy signals which contains overlapping segments of the Fourier spectrum. To overcome this deficiency, several previous studies [136–139] have proposed different approaches to improve the performance of EWT by employing an optimal technique for segmentation of the Fourier spectrum components with district boundaries. Gilles and Heal [136] proposed a parameterless scale-space technique to simply and efficiently decompose the signal modes. Similarly, an adaptive parameterless EWT (APEWT) method was introduced by Zheng et al. [137] to improve the performance of the EWT in properly segmentation of signals of a rotor system. The proposed method demonstrated superior fault diagnose performance compared to EMD-based methods. From a comparative study done by Liu et al. [138], EWT presented a more efficient approach in analyzing nonlinear signals of mechanical systems in comparison with the performance of EMD-based techniques. An efficient technique was used by Kedadouche et al. [139] for segmentation of the Fourier spectrum components of in the EWT in the analysis of the signals of bearing systems. The superiority of the proposed method in fault diagnosis of the bearing system compared to the performance of the EMD and EEMD was concluded in terms of the accuracy of the model estimation and computational cost by adopting a damage index based on the Kurtosis feature of the IMFs decomposed by the EWT. A hybrid use of EWT and MUSIC technique was employed by Amezquita-Sanchez [140] to present the time-frequency features of the analyzed signals with high-resolution. In the proposed method, the EWT with a wavelet filter bank was applied to the main signal frequencies determined by MUSIC in which the signal components had certain boundaries. The capability of EWT in capturing the fundamental frequency characteristics of distorted signals have concluded by several previous studies [141, 142]. A hybrid application of EWT in combination with HT, and STFT techniques was employed by Liu et al. [143] to obtain the time-frequency features of ultrasonic waves by performing a series of experimental tests. In the proposed method, the STFT used for time-history representation of the signal modes identified by EWT followed by the application HT for segmentation of the signal components. Despite extensive application of EWT for fault diagnosis in mechanical systems, EWT has been rarely used for damage detection of civil engineering structures. A combination of EWT and the second-order blind identification (SOBI) method was proposed by Yuan et al. [144] to obtain the modal characteristics of laboratory-scale framed structures with tuned mass damper (TMD). In this method, the EWT was able to effectively identify the fundamental frequencies of structures with very close certain distances separated by SOBI. To identify the modal properties of a spatial frame structure such as natural frequencies, mode shapes, and damping ratios, Xin et al. [145] used an improved EWT technique. The superiority of the improved EWT method in characterizing the signal components was found in comparison with the performance of Variational Mode Decomposition (VMD) technique. As another successful use of EWT combined with MUSIC and HT techniques were concluded by Amezquita-Sanchez et al. [146] in identifying the modal parameters of civil engineering structures such as natural frequencies and damping ratio. Mousavi et al. [147] demonstrated successful performance of EWT in combination with ANN algorithm for damage detection, localization and quantification in a steel truss bridge model based on the evaluation of several signal features including energy, root mean square (RMS), shape factor, kurtosis, and entropy extracted from the mode components by EWT.

5 S-Transform (ST)

The ST technique is a combination of Short Time Fourier Transform (STFT) and Continuous Wavelet Transform (CWT) techniques in which a Gaussian window with a frequency function [147, 148]. Besides, this technique can represent an improved form of wavelet transform (WT) with a modification on the adopted mother wavelet. While performing this modification causes a deficiency associated with neglecting the wavelet's admissibility criterion leading to zero mean of the wavelet. Accordingly, this technique cannot be considered as the CWT algorithm. The procedure of ST is based on shifting down the window for certain frequency ranges varying in time. The majority use of ST has been previously reported for fault identification of simple systems rather than large-scale structures. Pakrashi and Ghosh [149] concluded the efficiency of ST technique in analyzing noisy signals for fault diagnosis in a linear SDOF system through detecting any sudden stiffness changes, and crack localization in a steel beam with simple supports. The ST technique was employed by Ditommaso et al. [150] to analysis blast-induced vibration response of a 6-story RC building frame. The capability of the ST in damage localization in the structure was concluded through identifying the modal characteristics of the structure including the natural frequencies and mode shape parameters.

Tehrani et al. [151] presented a successful use of the ST for damage identification and localization in a mass-spring system. An improved ST method with time-frequency representation was proposed by Liu et al. [152] for damage detection in a simply-supported RC beam based on the analysis of the spikes occurred in the energy feature.

A ST-based signal processing technique based on the analysis of the peak responses of the modal parameters was introduced by Ponzo et al. [153] for damage identification in a 5-story structure. Furthermore, Ponzo et al. [154] used ST in damage detection and localization of RC frame subjected to an earthquake. A comparison study of using the ST and Band-Variable Filter techniques is evaluated by Iacovino et al. [155] for damage localization based on the detection of curvature variations. Numerical data retrieved from nonlinear FE models subjected to a damaging seismic excitation was used as a case study. Ditommaso and Ponzo [156] utilized the ST in a damage assessment strategy of a numerical and experimental RC frame models as shown in Fig. 17.

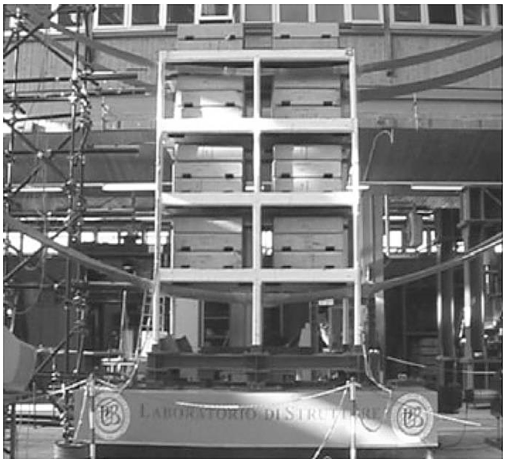
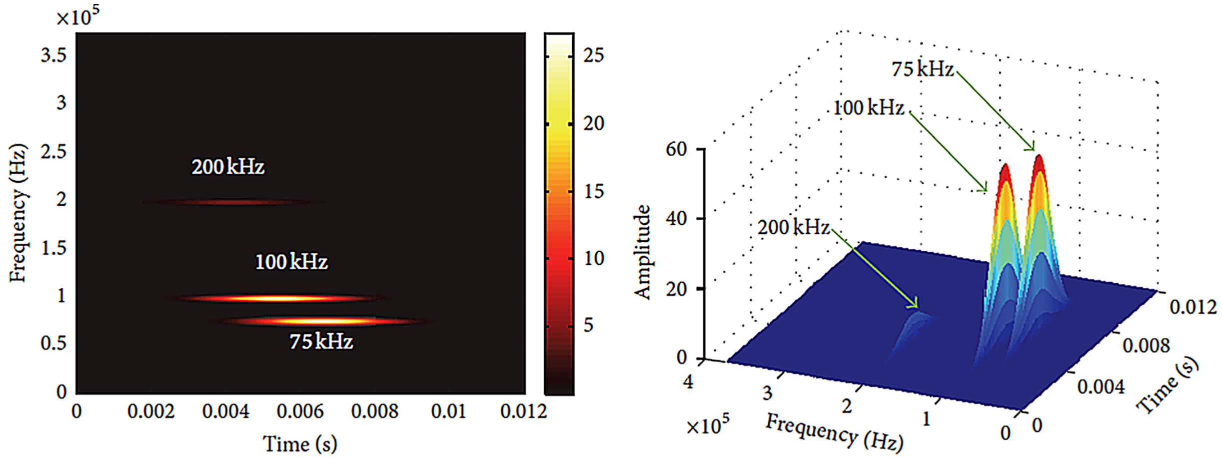


Fig. 17 Photo of a RC frame model on the shaking table– University of Basilicata [156]

To improve the performance of the ST technique in terms of computational resource capacity required for the analyzed data, the fast ST technique was proposed by Brown and Frayne [157]. This improvement is implemented by the fast ST technique by application of a down-sampling method in which a narrowed window is used to reduce number of samples adopted. An application of the Fast ST technique was reported by Ghahremani et al. [158] for damage identification in a 6-DOF structure under Northridge earthquake excitation. It was found that the Fast ST method can efficiently characterize the structural damage and its occurrence time through the analysis of the resonance frequencies of the structure. In addition, a combination of the Fast ST and CNN algorithm was employed to classify the damage severity of the predefined damage states for the structure.

6 Wigner–Ville Distribution (WVD)

The Wigner–Ville Distribution (WVD) technique is one of the time–frequency analyses which is known as a Cohen's class type representing high-resolution distributions in both time and frequency domains. Due to this capability of WVD, this technique feasible the analysis of nonlinear response signals of civil engineering structures. Although the primitive purpose of proposing this method was to solve the issue associated with statistical equilibrium in quantum mechanics [159], it has been extensively employed for SHM of structures. Despite the advantages of WVD such simplicity, high efficiency in the analysis of nonlinear signals, time-frequency distributions with high-resolution, needless to adopt any window function, etc. it may generate fictitious and spurious frequency due to its deficiency in representing any appropriate cross-term interference. The application of WVD in monitoring of mechanical systems has been extensively reported in the literature [160–163]. Besides, the WVD has been also used for extracting the natural frequencies of signals [164], and identifying the structural damage location using Non-Destructive Testing (NDT) technique by adopting ultrasonic guided waves [165]. A damage detection approach based on the use of WVD was proposed by Katunin [166] to be applied for FE models of aluminum beams. The proposed method was properly able to detect



(a)

(b)

Fig. 18 The SPWVD representation of the sample signal: (**a**) two-dimensional figure and (**b**) three-dimensional Figure [168]

the presence and quantify the severity of the damage in the beams. Qatu et al. [167] employed WVD technique for denoising purposes and present high-resolution distributions of the signal energy in time-frequency domains. It was found that this technique not only could identify the existence of the damage in in an aluminum plate, but also was capable to efficiently detect the damage location. A hybrid use of an improved WVD-based algorithm named Smoothed Pseudo WVD (SPWVD) and a peak-track algorithm was proposed by Wu et al. [168] for damage identification in a carbon fiber composite material. As a result, as shown in Fig. 18, the proposed approach could accurately represent the time-frequency distributions of the analyzed signal obtained from the damaged cases with high-resolution.

7 Conclusion

A comprehensive state-of-the-art review on the applications of signal processing techniques with time-frequency representations for damage detection, localization, and quantification in various structural and mechanical systems under environmental or controlled conditions, was presented in this paper. The progressive trend of time-frequency analysis techniques in solving the issues associated with the performance of traditional signal processing techniques was compared by clarifying the advantages and disadvantages of each technique. It was found that the EWT technique which is known as an improved WT-based technique, has advantages over EMD-based techniques in terms of solving mode mixing problem, improving low frequency resolution leading to inability of EMD in separating the signal components. These advantages enables the EWT to be efficient in analyzing high order nonlinear signals while reserving the original information of the analyzed signal and represent the results in time-frequency domains with high-resolution. However, EWT has a serious limitation in processing noisy signals which contains overlapping segments of the Fourier spectrum. To overcome this deficiency, it was recommended to use a combination of EWT and improved frequency-based techniques, such as MUSIC algorithm, which is efficient and capable to identify the signal components with certain boundaries.

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