Recent Advancements in Empirical Wavelet Transform and Its Applications

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This research is supported by Fundamental Research Funds for the Central Universities of China under Grant ZY1916.

ABSTRACT Empirical wavelets transform (EWT) is a fully adaptive signal-analysis approach, which is similar to the empirical mode decomposition (EMD) but has a consolidated mathematical theory, and is appealing in designing automatic algorithm for a variety of signal processing tasks. EWT first estimates the frequency components presented in the given signal, then computes the boundaries, and extracts the oscillatory components based on the computed boundaries. Because of the superb performance of the EWT in decomposing nonlinear and non-stationary signals, it has been successfully applied into a number of problems. The last 6 years have seen the development of EWT. This paper presents a general overview of the recent advancements made in research on the EWT algorithm and its state-of-the-art applications in a wide range of areas such as machine fault diagnosis, seismic data analysis, image processing, power system monitoring and medical disease diagnosis, which aims at providing some comprehensive references for reader concerning with EWT. We place emphasis on the applications of using such signal-analysis algorithm throughout with illustrative examples. Finally, the potential avenues for the future trends and directions associated with EWT are discussed.

INDEX TERMS Empirical wavelets transform, machine health monitoring, seismic data analysis, signal and image processing, power system signals analysis, medical disease diagnosis.

I. INTRODUCTION

In a variety of applications, the majority of signals are characterized by the nonlinearity and non-stationarity, which complicate the analysis procedure. Most of methods used for coping with such signals, e.g. wavelet transform (WT) [1] and empirical mode decomposition (EMD) [2], attempt to decompose the given signal into a series of different modes. And by analyzing the obtained modes, the interesting features can be extracted.

Wavelet transform is one of the widely used tools in the field of signal analysis and processing, it provides excellent results for analyzing the nonlinear and non-stationary signals. However, the fixed basis functions limit its application because it does not completely match all real signals. Empirical mode decomposition (EMD) is capable of decomposing a signal into a set of oscillatory components, which can be utilized for depicting some properties imbedded in input signal. The outstanding advantage of EMD is that the basic functions are derived from the given signal itself. Although EMD has obtained a great number of successful applications in different fields, the lack of mathematical theory is still an inherited defect.

To tackle those limitations, inspired by WT and EMD, Gilles proposed empirical wavelets transform (EWT) [3]. It has attracted much attention as one of the most powerful signal processing algorithm to deal with the nonlinear and non-stationary time series. The main idea of EWT is to determine the Fourier segments and then build a series of wavelet filters capable of extracting the different modes from the processed signal. EWT becomes adaptive when the Fourier segments are automatically determined. The empirical rule is to find all the local maxima of the spectrum and then use the center of the two adjacent local maxima as the boundaries of Fourier segments (Figure 1). For more detailed descriptions of EWT, the reader is requested to refer the paper by Gilles (2013) [3].

As a breakthrough in signal analysis and processing tech-
Empirical wavelet transform allows processing of data towards highly nonlinear and complex feature extraction by means of constructing an adaptive wavelet filter bank suited for signal decomposition.

In light of the advantage of EWT, this paper aims to provide a state-of-the-art review of EWT and its applications in a variety of fields, so that the reader concerning this topic can benefit from this study. The rest of paper is constructed as follows. Firstly, the latest advancement and successful application examples of EWT in relevant areas are summarized in Section 2, with the superiority of EWT techniques outlined. Then some research trends as well as potential future directions of EWT technique are discussed in Section 3. Finally, concluding remarks are given in Section 4.

II. APPLICATIONS TO SEVERAL FIELDS

A. MACHINE HEALTH MONITORING

Rolling bearings play a vital role in various industrial machines and are considered one of the most stressed parts in rotating machinery. In fact, bearings are inevitably damaged owing to overload and long-time operation. Especially, badly damaged bearings even destroy the whole system so that the expensive production shutdowns take place in manufacturing industry [5]. Therefore, machine health monitoring is of great importance to ensure a safe operation of a machine.

Nowadays, more and more signal processing techniques have been widely developed for machinery fault diagnosis.

For a complex bearing signal, a separation of modes is difficult based on traditional EWT. Kedadouche et al. (2016) [6] proposed to increase the frequency resolution to mask the modulation which is generated by a bearing defect. The better way to do this is to take only one shock that excites the natural frequencies and not considers the repetitive signal. The presented method successfully reveals the frequency and associated harmonics of the fault bearing.

In the study of Merainani et al. (2016) [7], the early detection of rolling bearing faults is introduced via EWT. Specifically, the Fourier supports of the analyzed signal are firstly detected and one builds the corresponding wavelet accordingly to those supports, finally filter the signal with the obtained filter bank. The envelope spectra analysis based on Hilbert transform proves its capacity to be a robust tool for the defect diagnosis in bearing using vibration signals.

To achieve feature extraction from nonlinear and non-stationary wind turbine condition monitoring signals, Shi et al. (2017) [8] proposed an enhanced EWT. Firstly, the envelope analysis of the signal spectrum is performed, then a hard thresholding is applied to trim the obtained envelope curve, so the principal frequency components contained in the signal can be readily identified, which are used for determining the number of EWT modes and the frequency boundaries of each mode.

Gao et al. (2017) [9] employed EWT to decompose acoustic emission (AE) signals into mono-components adaptively followed by calculation of the correlated kurtosis (CK) at certain time intervals of obtained components. Components with the largest CK value are thought of as the resonant frequency. Then the bearing fault characteristic frequencies are found by spectrum envelope. The flowchart of the proposed algorithm
Fourier transform, then the Fourier spectrum of the vibration approach, the raw vibration signal is firstly processed by fast accuracy in monitoring motor condition. In the presented approach, the raw vibration signal is firstly processed by fast Fourier transform, then the Fourier spectrum of the vibration is shown in Figure 2.

Xi et al. (2018) [10] investigated a rolling bearing fault detection method based on EWT. Firstly, the EWT is applied to rolling bearing vibration signals, then the normalized correlation coefficients of each order intrinsic mode function (IMF) with original signal are calculated, respectively. Next, the sensitive IMF is selected according to the calculated normalized correlation coefficient and kurtosis factor. Finally, the Hilbert envelope spectrum is utilized for bearing fault diagnosis.

Aiming at the problem to extract weak fault feature of wheelset bearing with the interference of the heavy noise, Deng and Liu (2018) [11] presented a self-adaptive frequency window EWT, where a sliding frequency domain window characterized by variable frequency bandwidth is introduced to segment the Fourier spectrum of fault signal of bearing. Meanwhile, water cycle algorithm (WCA) is used to determine the position of frequency window adaptively.

Taking into account eliminating the impact of noise interference or frequency dispersion in the detected signal, Dong et al. (2018) [4] combined local window maxima (LWM) algorithm with EWT to process the acoustic emission (AE) data for structural health monitoring (SHM) of composite materials. The key ideas of the proposed method are to search all the local maxima of the Fourier spectrum in a proper window, and then to determine the segmentation boundaries. Finally, the meaningful modes are obtained which are more related to the damage characteristics. The procedure of the proposed LWM-EWT is in Figure 3 and the improvements are marked in red area.

Eren et al. (2018) [12] used EWT to provide better accuracy in monitoring motor condition. In the presented approach, the raw vibration signal is firstly processed by fast Fourier transform, then the Fourier spectrum of the vibration data is adaptively divided into a series of segments, next the wavelet transform is applied to the obtained segments, finally inverse Fourier transform is implemented to extract time domain signal with the frequency band of interest for fault detection. The main advantage of the proposed method is the possibility of extracting only the segments of interest from the vibration signal for identifying both fault type and severity.

Since heavy noises and other unwanted strong vibration components exist in the Fourier spectrum of the signal for fault diagnosis of industrial railway axle bearing, conventional Fourier segments are challenged. Wang et al. (2018) [13] introduced the sparsity function to guide EWT so that the Fourier segments of a signal are automatically established, which is required in EWT for further envelope analysis with demodulation. The proposed method can correctly determine the resonant frequency bands for the squared envelope analysis that is beneficial to identify the different bearing defects.

Kong et al. (2019) [14] developed a meshing frequency modulation assisted empirical wavelet transform (MFM-EWT) framework for fault diagnosis of wind turbine planetary ring gear, which exploits an MFMindex assisted iterative backward-forward search algorithm to determine the Fourier spectrum segments for EWT. Then fault features are identified from the envelope spectrum of the fault-related modes extracted by MFM-EWT framework.

B. SEISMIC DATA ANALYSIS

Seismic data are able to reveal the useful information hidden in subsurface stratigraphy and lithology. Over the last 40 years, numerous methods have been proposed to analyze seismic signal such as short-time Fourier transform (STFT) [15], continuous wavelet transform (CWT) [16], S-transform [17], Wigner-Ville distribution (WVD) [18], matching pursuit (MP) [19] [20], empirical mode decomposition (EMD) [2] and its variants (ensemble EMD, EEMD; complete EEMD, CEEMD) [21] [22], and synchrosqueezing transform (SST) [23]. All these methods aim at achieving accurate analysis of non-stationary spectral variations and high-localization description.

Alegria et al. (2015) [24] presented a novel application of the EWT for seismic detection in ultra-low-frequency (ULF) geomagnetic signals, which comprises the ULF geomagnetic signals analysis via EWT, a statistical parameter based on variance and an automatic diagnosis through a FL system (Figure 4). The results show a better detection capability of seismic signals before, during, and after the main shock, which makes the proposal a more suitable and reliable tool.

Time-frequency analysis is a significant technology in seismic data processing and interpretation [25]. Inspired by EWT [3], Liu et al. (2016) [26] developed a novel EWT-based seismic time-frequency analysis approach suited for multichannel non-stationary signal for the purpose of seismic exploration. Results show that EWT can provide a much...
higher resolution in both time and frequency, which offers the potential in depicting geological information precisely.

Because of the lateral continuity being not taken into consideration for the traditional trace by trace based EMD or EEMD denoising method, Chen and Dong (2017) [27] proposed a new random noise attenuation technique based on EWT and dominant frequency criterion (DFC). EWT makes seismic signal decomposition adaptively, DFC solves the lateral continuity for seismic events. Field examples show successful performance to separate noise and seismic signal.

Lee et al. (2018) [28] designed a filter based on EWT method for coherent noise attenuation in high frequency marine seismic data, which are usually generated by the ship propeller. The main steps are as follows: EWT modes for each trace are computed and the ones with noise are selected, then the selected modes are zeros out and the remaining ones are utilized for reconstruction of the data.

Microseismic monitoring is an important procedure in enhancing natural permeability for the development of unconventional oil and gas reservoirs. Downhole microseismic data are often featured by low signal-to-noise ratio and high frequency, which brings some difficulty for noise reduction. [29] proposed a new downhole microseismic denoising algorithm by means of EWT combined with adaptive thresholding. Here, two threshold functions are set, the traditional hard thresholding for the modes that contain more useful signals to reserve the amplitude and the modified threshold for those modes which include less effective signals to maintain the continuity of the restricted signal.

C. SIGNAL AND IMAGE PROCESSING

In many applications, the signal is usually characterized by noise and non-stationarity, which makes the feature extraction complicated. Most of the methods, WT and EMD and its extensions, suitable for such signals attempt to decompose the original signal into a series of distinct modes and then the interesting features can be extracted from the obtained certain modes. However, these algorithms have more or less shortcomings, for example, requiring the priori information and lack of mathematical theory, which greatly limit their applications.

Instantaneous pitch, revealing some innate character of the speech, is regarded as one of the important physical aspects of speech. It is of great importance for application of speech synthesis and coding. Li et al. (2014) [30] proposed a new pitch estimator based on EWT and Hilbert transform which is capable of accurately detecting and estimating the time variation of pitch. Results show the effectiveness of the presented method in acquiring the instantaneous pitch.

In the field of signal processing, denoising is still a challenging problem. Francis and Muruganantham (2015) [31] presented an adaptive denoising technique aimed at ECG signal using EWT. This method is adaptive and is able to separate nonlinear and non-stationary components of the signals. Subsequently, Francis (2015) [32] introduced Gram Schmidt Orthogonalisation into EWT in order to make the obtained modes after EWT orthogonal. The usage of orthogonalisation increases the PSNR for denoising of images.

In image acquisition and transmission, the noise is inevitably introduced. Raj (2015) [33] developed a novel approach of image denoising using EWT and householder transform. The householder orthogonalization makes the IMFs obtained from EWT decomposition orthogonal and leads to an increase in the PSNR.

Pan sharpening is a technique of panchromatic image and multi-spectral image fusion in order to obtain an image with high spatial and spectral resolution, in which the panchromatic image characterized by single band with a wide range of visible spectrum and the multi-spectral image is composed of more than one spectral band. Moushmi et al. (2015) [34] demonstrated the application of EWT for the fusion of panchromatic image and multi-spectral image by simple average fusion rule, the flow diagram of the proposed method is exhibited in Figure 5. The aim of this study is to build composite image based on a high resolution panchromatic image and a low resolution multi-spectral image.

Identifying voiced segments in speech signals is a crucial step in the speech analysis field. In the past decade, a large number of researchers worked on this problem. [35] investigated the effectiveness of EWT for noise suppression in speech signals. Experimental results presented a considerable enhancement in the performance with EWT based preprocessing, which is beneficial to features extraction for subsequent classification of voiced and non-voiced speech signals.

The conventional EWT has a fact that an improper segmentation occurs in the frequency domain when noisy and non-stationary signals are analyzed. Hu et al. (2017) [36] proposed an enhanced EWT method (Procedure of the EEWT is in Figure 6), which uses order statistics filter (OSF) based the envelope approach to find the frequency peaks and applies three practical criteria to segment the spectrum of the processed signal. It takes the spectrum shape of the signal into account for frequency boundaries detection so that the
drawback of the EWT is ameliorated.

For many electronic imaging, people always have a strong desire to obtain the images with high resolution (HR). Image fusion technique allows the integration of different information sources, the purpose is to synthesize a single image with highest spatial resolution and spectral content. [37]

investigated a new methodology for reconstruction of HR images by fusion of multi-sensor images using EWT. Figure 7 shows the scheme of the proposed multi-sensor image fusion. At present, sensor fusion has emerged as an upcoming and promising research field.

D. POWER SYSTEM SIGNALS ANALYSIS

The electric power industry commonly consists in generation, transmission and distribution networks. The complexity of the power system brings a number of challenges to the quality of power, which is often associated with normal operation of sophisticated electrical equipment. With the growing importance of maintaining power quality (PQ), it has become essential to quickly quantify and analyze the PQ disturbances. Adverse of poor quality power usually results in loss of productivity [38]. Therefore, various processing techniques should be adapted to detect and analyze the power signal that is characterized by the nonlinear and non-stationary.

Since most of power quality (PQ) is featured by noisy and non-stationary in nature, an advanced signal analysis method is required to accurately decompose the power signal. Thirumala et al. (2015) [39] demonstrated an application of EWT for the estimation of single-phase and three-phase power-quality indices (PQIs). The results confirm that the EWT efficiently extracts the mono-component from the signal with power-quality disturbances and thereby accurately estimates the PQIs.

Power quality (PQ), referring to an especial electromagnetic phenomenon which the voltage or current of power grid deviates from the standard sinusoidal waveform, has become a vital issue for the power utilities and users. The wide use of nonlinear load results in the PQ deterioration. In order to
improve PQ, the detection of PQ is essential. Chen et al. (2017) [40] proposed a hybrid algorithm for detecting PQ disturbances, in which EWT combines Hilbert transform to analyze the simulated power signal. The presented method can be viewed as a viable alternative for detecting the power quality disturbances.

Occurrence of harmonics, one of the major power quality issues, is inevitable due to the nonlinear load, which may lead to the adverse effects such as presence of resonance in power system, overheating, overloading of neutral wire in three phase systems, and so on. Therefore, it is very essential for filtering power system harmonics. Jain et al. (2017) [41] investigated the harmonic estimation based on EWT algorithm, separating the fundamental and harmonic contents from the composite current or voltage waveform, which aims to conduct the cancellation of harmonics using active power filter.

Time-frequency based power quality (PQ) indices estimation is very vital to assessment of time-varying electrical disturbances. This accurate estimation contributes to identification of the disturbance and its source. Thirumala et al. (2017) [42] presented a generalized EWT (GEWT), which is to estimate the actual frequencies contained in the power signal having disturbances. The major contributions of this work comprise the accurate extraction of the fundamental frequency content, the filtering via adaptive Fourier segmentation and the fast estimation of time varying indices.

Accurate electric load is of great importance to successful implementation of smart power grid. Zhao and Li (2018) [43] applied EWT-SimpleMKL to short-term power load forecasting, where the EWT firstly is used to decompose the original power load data and then the obtained modes after decomposition are combined with SimpleMKL algorithm to construct the different prediction models. The proposed method shows that EWT has better forecasting performance for power load data.

### E. MEDICAL DISEASE DIAGNOSIS

In order to increase prediction reliability, it is crucial to develop and implement an automated diagnosis system for diverse diseases such as glaucoma, heart attack and Parkinson’s disease that allows clinicians to monitor the health status of the patients in order to determine when treatment should be performed. The detection and classification for disease based on extracted feature from signals are significant for prediction, and the EWT has demonstrated its capability to analyze the digital medical signals.

The examination of the ECG signals has been widely used to diagnose many cardiac diseases, however, acquisition of these signals usually results in large volumes of data. Therefore, efficient data compression algorithms with respect to ECG signals are urgently needed to transmit and store them. Various methods have been proposed for ECG data compression. Kumar and Saini (2014) [44] adopted a hybrid framework based on EWT and discrete wavelet transform (DWT) for compression and reconstruction of ECG signals.

The arterial blood pressure (ABP) pulse provides a great deal of information regarding cardiovascular circulation system. Arterial blood pressure pulses are often utilized to monitor the health status of cardiovascular system. Singh and Sunkaria (2015) [45] presented a new algorithm for the detection of onsets in arterial blood pressure signals via EWT, which explicitly constructs an adaptive wavelet filter bank in order to decompose a given signal to different modes. The flowchart of the proposed approach is displayed...
in Figure 8, which includes three stages. In the first stage, the ABP pulse is decomposed into a series of modes by EWT. In the second stage, the mode characterized by the frequency of pulse is investigated. The last stage is making detection.

Glaucoma is an eye disease, caused by the increased fluid pressure in the optic nerve, which may lead to loss of vision if it is not treated properly. In order to achieve glaucoma diagnosis in eyes, the robust features selections are necessary. Beaula et al. (2017) [46] developed an automated diagnosis system for glaucoma based on EWT and correntropy features. In EWT decomposes the digital fundus image into various frequency bands and correntropy features are extracted from decomposed EWT modes. Then the obtained features are normalized and ranked based on significant criteria. Finally, the Least Squares Support Vector Machine (LS-SVM) is employed to conduct the classification of normal and glaucoma images. Figure 9 shows the diagram for automated glaucoma diagnosis. On the other hand, the extensively used methods for the diagnosis of glaucoma are Heidelberg Retinal Tomography (HRT), Scanning Laser Polarimetry (SLP) and Optical Coherence Tomography (OCT), however, they are costly and commonly used by the experienced clinicians. Hence, Kirar and Agrawal (2017) [47] developed a new system for automated diagnosis of glaucoma, where the 2D EWT is employed to decompose the glaucomatous digital fundus image and the entropy feature extracted from decomposed EWT components. The block diagram of the proposed methodology is shown in Figure 10.

Phonocardiogram (PCG) signals, a kind of electronic recording of vibratory sounds, can provide most valuable diagnostic information for evaluating the heart disease. However, detection and classification of different heart murmurs are specially challenging issue with respect to PCG signals. Varghees and Ramachandran (2017) [48] proposed a novel PCG signal description and murmur classification algorithm that is suitable for automatic detection and classification of heart sounds and murmurs. Figure 11 illustrates a simplified diagram of PCG signal depiction and murmur classification approach. Firstly, the EWT is employed to decompose the PCG signal for identifying heart sounds from heart murmurs, then murmur classification is carried out based on the extracted the essential clinically relevant heart sound and murmur parameters. Results demonstrate that the presented approach outperforms the existing heart sound segmentation and murmur classification methods.

Parkinson’s disease (PD) has affected a significant number of people till now. In order to develop an effective diagnostic system, various algorithms have been proposed to identify healthy individuals from the ones with PD. However, most
FIGURE 11. Block diagram for detection and classification of murmurs (Varghees and Ramachandran, 2017) [48].

FIGURE 12. Flow chart of the proposed approach (Qi et al., 2018) [49].
FIGURE 13. Overall workflow for modified EWT-ARIMA (Shaari et al., 2018) [51].

of works mainly focus on a binary classification in the early PD stage. Qi et al. (2018) [49] presented a multiclass classification algorithm regarding Parkinson’s disease severity based on EWT, which aims at detecting and classifying PD utilizing the signals from wearable motion and audio sensors. The findings demonstrate that the proposed method has the ability to differentiate PD from non-PD subjects and achieves the classification accuracies of more than 90%. Figure 12 shows the flow chart of the proposed method which is composed of data collection, signal processing and decomposition, feature extraction and classification.

F. OTHER APPLICATIONS

In addition to the aforementioned applications, EWT has also been extended to other fields due to its potential in analyzing the nonlinear and non-stationary signals. This section is intended to summarize the results.

With the fast growth of wind energy, the accurate and effective prediction techniques for short-term wind speed are urgently required, which are closely related with wind energy plant operations. Most of methods focus on point wind speed forecasting, however, in recent years, hybrid approaches have been increasingly emerged because of their accuracy and stability. Hu and Wang (2015) [50] proposed a hybrid forecasting algorithm to predict short-term wind speed, which includes EWT, partial auto-correlation function (PACE) and Gaussian process regression (GPR). In the presented method, EWT is employed to decompose the short-term wind speed data into a series of modes, PACT is used to identify the partial autocorrelation of the obtained data that can be reconstructed by the selected modes, and the established GPR is utilized to predict the distribution of the future wind speed.

Drought takes place across the word and can be destructive to lives of people in an area. Therefore, drought forecasting plays a significant role in preparing for drought and corresponding remedy. Shaari et al. (2018) [51] investigated the combination of EWT and Auto Regressive Integrated Moving Average (EWT-ARIMA) based on clustering analysis in order to forecast drought in Arau using Standard Precipitation Index (SPI), which was developed by McKee et al. (1993) [52] as a drought indicator. EWT is employed to generate Intrinsic Mode Functions (IMFs) that are used to create ARIMA models. Fuzzy c-means clustering is used to create the clusters based on the instantaneous frequency by Hilbert Transform. Figure 13 shows the overall process for EWT-ARIMA clustering analysis.

III. DISCUSSIONS AND OUTLOOK

Empirical mode decomposition (EMD), proposed by Huang et al. (1998), is an attractive signal analysis tool suited for nonlinear and non-stationary signals. Contrary to wavelet transform, EMD does not require a prior basis and results in complete signal decomposition, which means the input signal can be reconstructed by summing all modes and no loss of information occurs. Even though EMD offers several excellent features, some inherited defects still limit its wide application such as mode mixing and end-point artefacts [53]. To tackle the negative features related with EMD, two variants, ensemble empirical mode decomposition (EEMD) [21] and complete ensemble empirical mode decomposition (CEEMD) [22], are introduced. In essence, EEMD is EMD combined with noise stabilization and Gaussian white noise can effectively reduce mode mixing [21] [54]. However, EEMD leaves another question, that is, summing all intrinsic mode functions (IMFs) does not perfectly reconstruct the original signal [22] [55]. CEEMD is a robust extension of EMD, which depends on different realizations of signal plus noise and leads to complete signal reconstructions. Unfortunately, the residual noise originated from the decomposition process will inevitably happen in the modes after CEEMD, which has a strong influence on signal analysis.

The empirical wavelet transform (EWT) is a novel adaptive algorithm suitable for handling the nonlinear and non-stationary signals, which inherits the advantage of WT and EMD. The key idea is how to build an appropriate wavelet filter bank in order to segment the Fourier spectrum of the analyze signal. Recently, EWT has been successfully applied in various areas such as machine fault diagnosis, seismic data...
analysis, image processing, power system monitoring and medical disease diagnosis. However, differing from EMD and its variants that is fully data-driven and does not need any prior information associated with the given signal, the EWT decomposition requires to pre-set the number of modes and frequency boundaries of each mode. In fact, this is always difficult due to lack of prior knowledge about the analyzed signal and the inappropriate parameters will lead to the inaccurate decomposition of the signal. To address this issue, much effort has been spent to improve the conventional EWT. Shi et al. (2017) [8] developed a feasible and efficient spectrum segmentation algorithm by the aid of the envelope spectrum analysis in association with a hard thresholding technology. Yue et al. (2017) [36] used order statistics filter (OSF) based the envelope approach to find the frequency peaks and applied three practical criteria to segment the spectrum of the processed signal. Deng and Liu (2018) [11] introduced a sliding frequency window characterized by variable frequency bandwidth to achieve a self-adaptive frequency window EWT. These solutions have greatly improved the defects of traditional EWT to some extent.

In previous sections, we have summarized reported studies on using EWT in many applications. Based on the aforementioned investigations, it is found that several aspects can be done further with regard to EWT. Firstly, ones are making a great effort to develop the enhanced EWT in order to overcome the shortcomings of traditional EWT. Hence, there is a need for algorithm that can handle the data-driven selection of the main parameters for EWT. Secondly, the combination of EWT with other techniques has attracted more attentions, which could also improve the performance of the original EWT, and the hybrid strategy has achieved the better performance for some certain issues. Finally, almost all considered algorithms in this review are single-trace and thus one-dimensional methods. However, the multidimensional signals are very common. We anticipate that the multicomponent and multidimensional algorithm for EWT can be applied in practice.

IV. CONCLUSIONS

As an adaptive signal decomposition algorithm, empirical wavelet transform (EWT) has shown superiorities in both signal analysis and feature extraction. The paper attempts to summarize and review the recent research and development of EWT, which aims to provide some comprehensive references for readers in this field. In this study, the potential benefit and successful application examples of EWT are discussed, especially in the areas of machine fault diagnosis, seismic data analysis, image processing, power system monitoring and medical disease diagnosis. Such an advantage makes the EWT a potentially powerful tool for analyzing the nonlinear and non-stationary signals. In addition, the problem of EWT and the potential future trends are also pointed out. We hope that this study can help reader to obtain basic knowledge about EWT, quickly apply EWT in practice and further develop EWT.

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