ANALYSIS OF INSTANTANEOUS FREQUENCY FOR STRUCTURE CONDITION TRACKING USING TIME-FREQUENCY REPRESENTATION: COMPARATIVE STUDY

Chuanyue Zhang[1], Yanliang Xu[1], Ahmed Silik[2, 3], Hanxi Li[4], Mohammad Noori[5], Wael A. Altabey[6]
[1]Nanjing Highway Development Center, P.R. China; [2]Nanjing Zhixing Information Technology Co.,Ltd., P.R. China; [3]Nyala University, Sudan; [4]University of Sydney, Australia;
[5]California Polytechnic State University, USA; [6]Alexandria University, Egypt
mnoori@outlook.com, wael.altabey@gmail.com

Abstract. Damage causes the dynamic structural responses of civil engineering structures to change from linear to nonlinear. It can be challenging to break down signals and identify features, mainly when the data is generated by a nonlinear system and is nonstationary. Under heavy loads and during routine operations, civil structures have been seen to exhibit nonlinear dynamic characteristics. To assess progressive damage, it is necessary to characterize the time-varying attribute of the structure's nonlinearity and consider how the frequency and amplitude contents of nonstationary vibration responses change over time. The properties of a nonstationary signal cannot be properly described by either time analysis or frequency analysis alone. When measured data include structural damage occurrences, it is critical to extract as much information about the damage as possible from the data. To create a reliable damage detection method that captures damage progression using vibration data gathered by sensors, this work examines the instantaneous frequency (IF) representation utilizing time-frequency distributions of the energy density domain based on short-time Fourier transform, wavelet transform, Hilbert-Huang transform, Wigner-Ville distribution, and synchrosqueezed transform. Each technique capability is validated using various experimental data. It is found that both the synchrosqueezed transform and Wigner distribution proved to be the best performance in terms of IF tracking and showed particular promise due to their spectral energy concentration with the synchrosqueezing transform outdoing other techniques in terms of computation precision.

Keywords: frequency, instantaneous, nonstationary, damage, wavelet.

Introduction

Civil and mechanical engineering structures suffer damage throughout their lives due to variations in the performance of the materials, loads, and other uncontrollable factors [1; 2]. Their vibration responses can be categorized as stationary or nonstationary by varying the statistical features over time. Thus, time-frequency (T-F) domains are used to study time-varying signals [3; 4]. The time-varying responses are frequently irregular in amplitude and frequency over time [5]. The T-F analysis (TFA) is needed to extract the dynamic responses' time-varying features [3]. TFA combines the advantages of analysis in the time and frequency for nonstationary signals [6; 7]. The T-F method has been extensively used in various fields; it provides analytical tools for dynamic structural analysis and damage diagnosis [8; 9]. Engineering research on damage detection often focuses on linear and bi-linear T-F distribution [10]. TFA -based damage identification is an essential component of health monitoring research and has been extensively used [11; 12]. The most popular energy density distributions are short-time Fourier transforms (STFT), Wigner distributions, and generalized Wigner distributions (GWD) [3; 13]. Significant artifacts may be seen in each distribution along the frequency axis. However, it is understood that only WD is free from artifacts when dealing with linear frequency-modulated signals [7]. Wavelet is an effective tool for spilling the signal in the T-F domain[14; 15]. In[5], four signals with various frequencies were used to study nonstationary signals using the continuous wavelet transform (CWT) [16] and synchrosqueezing transform (SST) [17]. Recently, algorithms like an empirical mode decomposition (EMD) and Hilbert transform (HT) [18] have been used to decompose a signal more accurately than the wavelet. So it can detect any discontinuity in the vibration data [19]. More recently, the approach based on HT and EMD has been used to identify linear structures effectively [20] and was taken to identify, localize, and determine the damage in structures [21]. They used fractality dimensions based on nonlinear dynamics and SST to discover and diagnose the damage in the structures.

This paper proposes instantaneous frequency (IF) based on various T-F representations to assess and track the structure conditions. Experimental data from the bridge, located across the Lieshi River, Rugao city, Jiangsu province, and data from the shaking table test of a six-story RC frame building are used to validate the proposed method.

Bilinear time-frequency distribution (TFD)

The signal energy can be determined using the bilinear TFD. The bilinear TFD has inherent cross-terms that prevent it from satisfying linear superposition. It is further subdivided into WVD-derived Cohen bilinear TFD and affine bilinear TFD. The bilinear TFA was developed from the energy spectrum, and WVD most distributions [22]. It contains amplitude and phase information. Cross-term interference in multicomponent signals may result, which is a fundamental characteristic of bilinear TFD [23]. GWD-LWD is introduced to decrease the artifacts as in [24].

$$\text{WVD}_s(t, f) = \int s\left(t + \frac{\tau}{2}\right) s^*\left(t - \frac{\tau}{2}\right) e^{-j2\pi f\tau} \, d\tau \ . \tag{1}$$

Here asterisk "*" denotes the complex conjugate and Eq. (1) avoids choosing the T-F resolution in the linear T-F representation and does not include window functions.

Hilbert transform (HT)

HT is a technique to project a real signal onto the imaginary axis, enabling instantaneous amplitude and frequency measures. HT of the signal $x(t)$ is expressed as in [15]:

$$\mathcal{Y}(t) = \mathcal{H}[x(t)] = \frac{1}{\pi} p.v \int_{-\infty}^{\infty} \frac{x(\tau)}{t - \tau} d\tau \ , \tag{2}$$

The notions of instantaneous amplitude and frequency for general signals are not well defined [25]. Only monocomponent signals (MONS) can be used in HT to estimate a signal's IF. Since HT is developed to detect nonlinearity, it can be used in nonlinear structures [25]. HT and EMD are combined to create Hilbert–Huang Transform (HHT), which works well for nonstationary data. HHT well acquires instantaneous amplitude, frequency and power [28], while EMD breaks down signals into MONS /IMFs. Since MONS are frequently thought as being close to periodic and sinusoidal, it is possible to derive IF from IMFs. To realize HHT for real applications, an FIR filter is used to estimate HT.

Instantaneous frequency presentation

Decomposition into sinusoidal components does not work effectively for nonstationary signals, and frequency loses its effectiveness for such signals, requiring using a parameter that considers their time-varying nature [27]. This gave rise to the IF idea, a time-varying related to average frequencies [28]. Only MONS are used in HT to estimate IF and it has an analytic association as [25]:

$$z(t) = a(t) e^{j\varphi(t)} . \tag{3}$$

Methodology

The overall procedure of the proposed method is shown in Fig.1. It is divided into various tasks as: 1) obtain data based information for the intact and current condition to be analysed under different environmental conditions; 2) apply an adequate filter to eliminate the noise and normalized to remove the effect surrounding variation and data segmentation; 3) exploratory analysis to do accurate and reliable data analysis; 4) using various techniques based time frequency analysis represented in STFT, WT, EMD, HHT, and WVD to decompose the signals. After the decomposition, the Hilbert spectrum can be obtained by using HHT on each IMF; 5) map the time frequent representation and extract the instantaneous frequency; 6) compare instantaneous frequency based various techniques objectively in term of spectral energy concentration and computation precision.
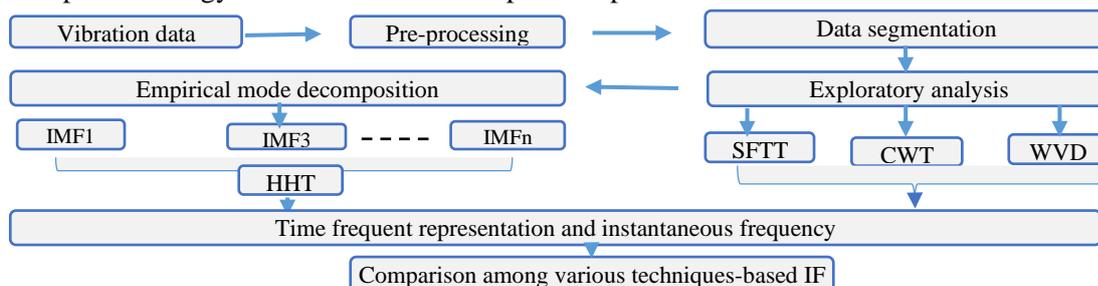

Fig. 1. **Overall diagram of the work methodology**

Any possible deviation in the signals of different structure states, is interpreted as a damage increment through the instantaneous frequency. Although the steps are listed in order, we may jump between them depending on the project.

Result analysis and discussion

This paper provides insights into IF based on STFT, WT, EMD, HHT, and WVD in structural vibration analysis. To do this, first the vibration signals are pre-processed, segmented and then visualized in time and frequency domain, as shown in Fig. 2. Fig. 2 shows the acceleration and the corresponding spectrums. It is noted that the records are time-varying, subjected to abrupt changing, and noise. The spectrums show the various dominant frequencies in the responses and how much data lies within each specific band over frequencies and how PSD distributes over them.
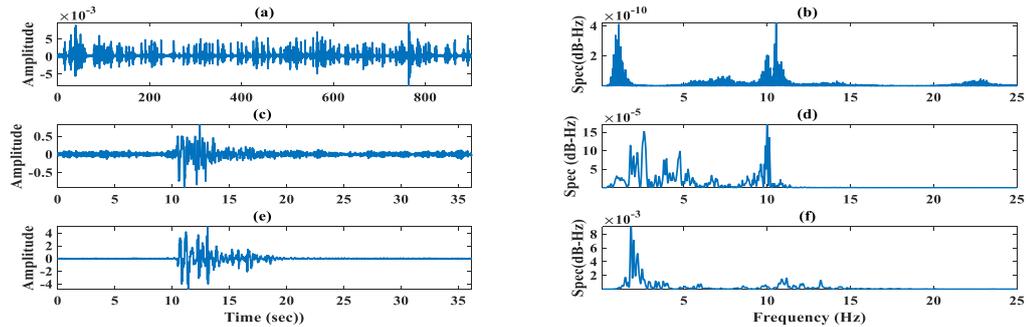

Fig. 2. **Acceleration and spectrums, (a,b) bridge, (c,d) frame-intact, and (e,f) frame-damaged**

Method assessment for tracking of time-varying frequencies

This section studies how different methods can capture the time-varying frequency in the vibration response. Fig. 3 shows IF distributions for HT, STFT, and SST. HT fails to calculate IF because the signal is not monocomponent, while SST shows good results compared with others. HT needs to perform EMD to compute IMFs and residual signals. Figs.4 shows IMFs obtained from EMD for the data obtained from the bridge. Normalized IMFs are used to compute the IF-based HT.
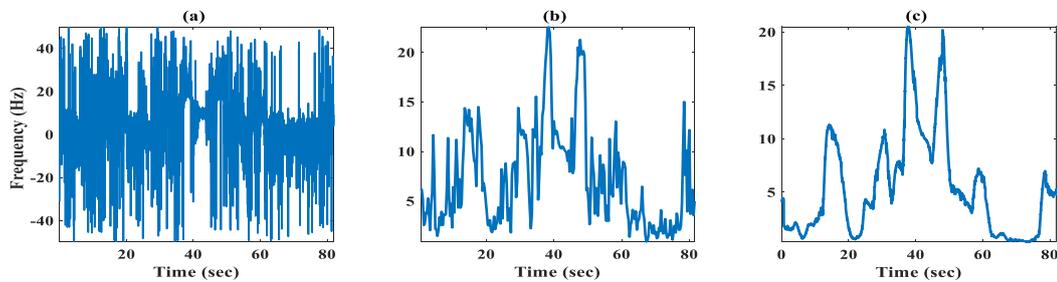

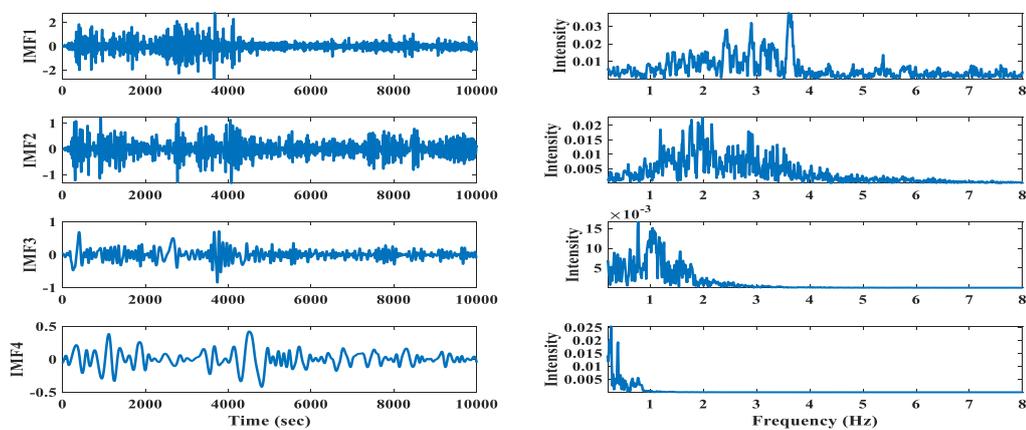Fig. 3. **Overall diagram of the work methodology**

Fig. 4. **IMFs of the acceleration response methodology**

Fig. 5, 6, and 7 show various T-F representations with IF to track the energy distribution. The bright colour at each point is associated with the magnitude of the coefficient, representing the signal's energy distribution. Note that the spectrogram based STFT cannot distinguish the different IFs when the frequencies are low or close together and its performance is slightly poorer compared to other techniques due to its restricted frequency resolution, which is a result of the analysis window's fixed breadth. SST shows a T-F representation that accurately captures IF. It has largely compensated for the spread in TF introduced by the wavelet filters. Though there are some fluctuations of identified IFs, SST can still precisely reflect the trend of changing frequency. SST has squeezed the relatively broad peaks in T-F into narrow ridges. You can extract these ridges and reconstruct the individual components from the T-F ridges. To validate the accuracy of the proposed technique, acceleration data obtained from the shaking table test of a six-story RC frame building conducted in E-Defense, Japan, is used. The data and corresponding spectrum response are shown in Fig. 2.
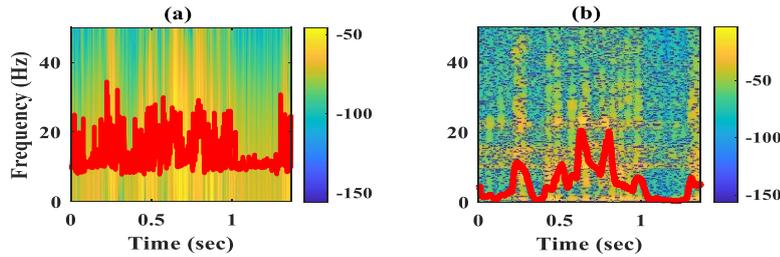

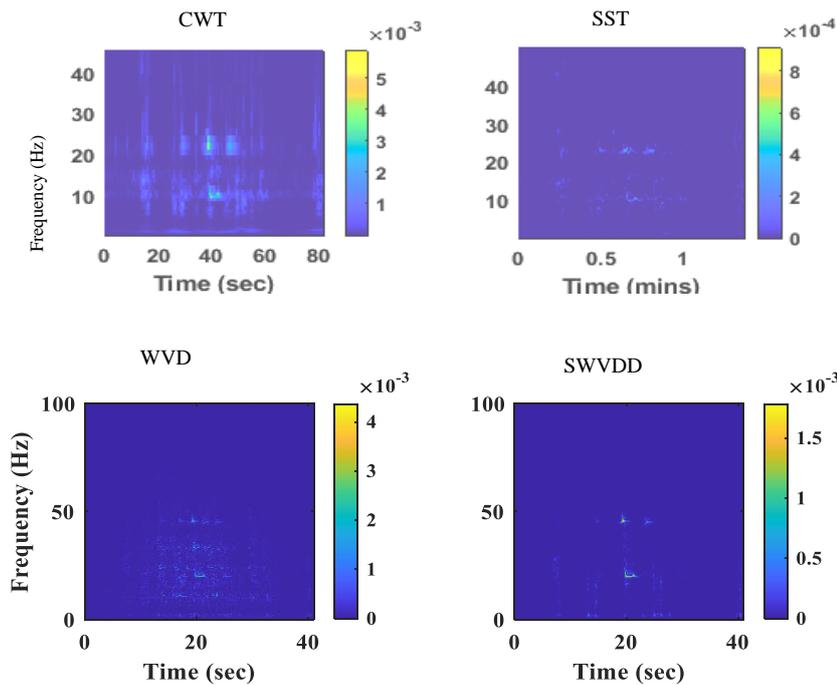Fig. 5. **T-F representation with IF, (a) STFT, (b) SST**
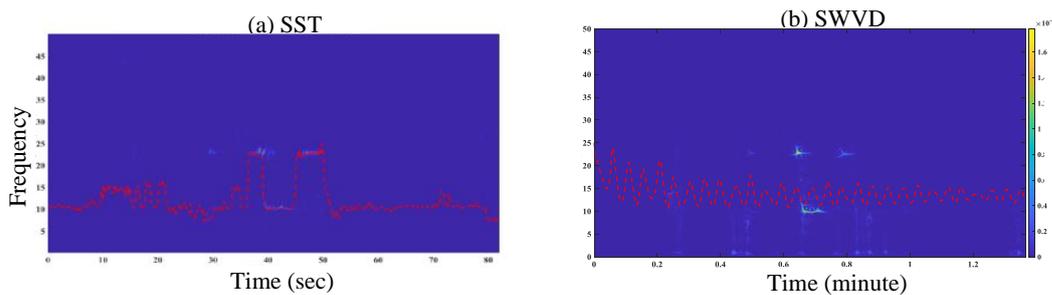

Fig. 6. **Various T-F representations**

Fig. 7. **T-F representation with IF, (a) SST, (b) smoothed Winger distribution**

IF-based SST is used to investigate the change in IF to track time-varying frequencies to detect and locate the damage. Fig 8 compares IF of the undamaged and damaged states. There is a significant variation. The distinguishable difference between two IF signals can be used as an indicator for condition assessments. It has been shown that SST work better in capturing frequency shifts as a frequency component is compressed and localized over time.
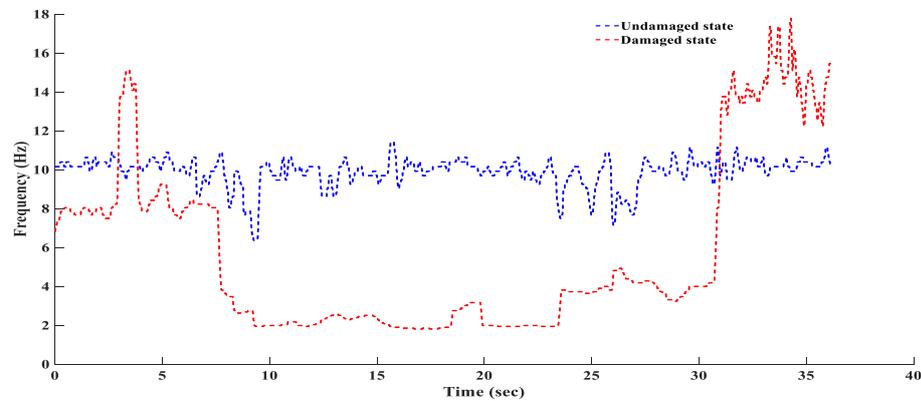

Fig. 8. **Comparison of IF of undamaged and damaged states**

Conclusions

This study investigated the potential of various T-F representation techniques for tracking and interpreting the instantaneous frequency (IF) as damage feature for civil structure condition assessment. Also, it discusses the IF concept, its definitions, and the correspondence between the various mathematical models formulated for IF representation. Particularly, IF based STFT, CWT, SWVD, and SST are compared to highlight the superiority. The various techniques feasibility and effectiveness for tracking IF are verified using experimental acceleration data from a bridge and frame building. Also, experimental data sets were utilized in our comparisons. The results from this investigation show that both SWVD and SST methods could be performed significantly better in terms of spectral energy concentration than other methods, with SST outdoing other techniques in terms of convergence speed and computation precision. Also, it is shown that IF is a good descriptor of structure condition assessment. The SST technique is also adaptive to the data, i.e. the prior nature of the signal was not necessary to be known and it provides an efficient way to characterize signals whose frequencies change in time as well as non-linear characteristics and track the time-varying frequencies in real data and capturing frequency shifts as a frequency component. The SST technique not only enhances the correctness of instantaneous frequency identification, but also clearly describes the relations of changing frequency versus the time. As the name implies, the SST technique can squeeze wavelet components to refine and sharpen T-F curves, and a more accurate IF is obtained as a result. Hence, it is concluded that SST can successfully identify IF of time-varying and nonlinear structures, compared with other standard TFR methods. Finally, although SST gave relatively better performance among other T-F analysis approaches, it can be concluded that either SST or SWVD is appropriate for time-varying frequencies in real data analysis to track IF which can be used as a good descriptor of structure condition assessment. A fundamental contribution of this study is the introduced technique based IF that can be used for stationary ambient and nonstationary severe motion responses to assess various structural conditions.

Author contributions

Methodology, A.S., M.N. and W.A.A.; software, A.S., M.N. and W.A.A.; validation, M.N. and W.A.A.; investigation, M.N. and W.A.A.; data curation, Z.C., X.Y. and L.H.; writing – original draft preparation, A.S.; writing – review and editing, M.N., W.A.A. and L.H.; visualization, A.S., M.N. and W.A.A.; funding acquisition, Z.C., X.Y. and L.H.; All authors have read and agreed to the published version of the manuscript.

References

[1] Ghiasi R. et al., "Structural Assessment under Uncertain Parameters via the Interval Optimization Method Using the Slime Mold Algorithm," Appl. Sci., vol. 12, no. 4, pp. 1-21, 2022, DOI: 10.3390/app12041876.

[2] Yuchao M., Weiming Y., Haoxiang H., Kai W. "Damage detection based on cross-term extraction from bilinear time-frequency distributions," Math. Probl. Eng., vol. 2014, 2014.

[3] Yan J., Laflamme S., Singh P., Sadhu A., Dodson J. "A Comparison of Time-Frequency Methods for Real-Time Application to High-Rate Dynamic Systems," Vibration, vol. 3, no. 3, pp. 204-216, 2020, DOI: 10.3390/vibration3030016.

[4] Silik A. et al., "Dynamic wavelet neural network model for damage features extraction and patterns recognition," J. Civ. Struct. Heal. Monit., no. 0123456789, 2023, DOI: 10.1007/s13349-023-00683-8.

[5] Olav B. "Instantaneous Frequency in Electric Power Systems Wavelet vs Hilbert Huang," no. September, pp. 7-8, 2016, DOI: 10.13140/RG.2.1.5032.7280.

[6] Wang Z. C., Ren W. X., Chen G. Time-frequency analysis and applications in time-varying/nonlinear structural systems: A state-of-the-art review, vol. 21, no. 10. 2018.

[7] Brotherton T., Pollard T., Jones D. "p Jix," pp. 4-7, 1992.

[8] Papadrakakis M., Charmpis D. "Damage Identification of Structures Using Instantaneous Frequency Changes," Researchgate.Net, no. May, 2007, [online] [11.03.2023] Available at: http://www.researchgate.net/publication/256543881_DAMAGE_IDENTIFICATION_OF_STRUCTURES_USING_INSTANTANEOUS_FREQUENCY_CHANGES/file/60b7d5234577d13099.pdf

[9] Silik A., Noori M., Altabey W. A., Ghiasi R. "Selecting optimum levels of wavelet multi-resolution analysis for time-varying signals in structural health monitoring," Struct. Control Heal. Monit., 2021, DOI: 10.1002/stc.2762.

[10] Cohen L. "Time-Frequency Distributions: A review," Proceedings of the IEEE. pp. 941-981, 1989.

[11] Farrar C. R., Jauregui D. A. "Comparative study of damage identification algorithms applied to a bridge: II. Numerical study," Smart Materials and Structures. 1998. DOI: 10.1088/0964-1726/7/5/014.

[12] Wang Z. C., Ren W. X., Chen G. "Time-frequency analysis and applications in time-varying/nonlinear structural systems: A state-of-the-art review," Advances in Structural Engineering. 2018. DOI: 10.1177/1369433217751969.

[13] Feldman M. "Non-linear free vibration identification via the Hilbert transform," J. Sound Vib., 1997, DOI: 10.1006/jsvi.1997.1182.

[14] Silik A., Noori M., Altabey W. A., Dang J., Ghiasi R., Wu Z., "Optimum wavelet selection for nonparametric analysis toward structural health monitoring for processing big data from sensor network: A comparative study," Struct. Heal. Monit., 2022.

[15] Silik A., Noori M., Altabey W. A., Ghiasi R., Wu Z., Dang J., "Evaluation of analytic wavelet parameters effet for data analyses in civil structural heath monitoring," Int. Conf. Struct. Heal. Monit. Intell. Infrastruct. Transf. Res. into Pract. SHMII, vol. 2021-June, no. January 2022, pp. 813-818, 2021.

[16] Silik A., Noori M., Altabey W. A., Ghiasi R., Wu Z., "Comparative analysis of wavelet transform for time-frequency analysis and transient localization in structural health monitoring," SDHM Struct. Durab. Heal. Monit., 2021, DOI: 10.32604/sdhm.2021.012751.

[17] Jiang Q., Suter B. W. "Instantaneous frequency estimation based on synchrosqueezing wavelet transform," Signal Processing, vol. 138, no. February 2018, pp. 167-181, 2017, DOI: 10.1016/j.sigpro.2017.03.007.

[18] Fontugne R., Borgnat P., Flandrin P. "Online Empirical Mode Decomposition," 2017. DOI: 10.1109/ICASSP.2017.7952969.

[19] Altabey W.A., Noori M., Li Z., Zhao Y., Aval S.B.B., Farsangi E.N., Ghiasi R., Silik A. A Novel MRE Adaptive Seismic Isolator Using Curvelet Transform Identification. Multidisciplinary Digital Publishing Institute, MDPI, 2022.

[20] Shi Z. Y., Law S. S. "Identification of linear time-varying dynamical systems using hilbert transform and empirical mode decomposition method," J. Appl. Mech. Trans. ASME, vol. 74, no. 2, pp. 223-230, 2007, DOI: 10.1115/1.2188538.

[21] Kulia G., Molinas M., Lundheim L., Larsen B. B. "Towards a real-time measurement platform for microgrids in isolated communities," 2016. DOI: 10.1016/j.proeng.2016.08.070.

[22] Najmi A.-H. "The Wigner Distribution: A Time-Frequency Analysis Tool," Johns Hopkins APL Tech. Dig., vol. 15, no. 4, p. 298, 1994, [online] [11.03.2023] Available at: http://www.jhuapl.edu/techdigest/views/pdfs/V15_N4_1994/V15_N4_1994_Najmi.pdf

[23] Hlawatsch F., Boudreaux-Bartels G. F. "Linear and quadratic time-frequency signal representations," IEEE Signal Processing Magazine, vol. 9, no. 2. pp. 21-67, 1992. DOI: 10.1109/79.127284.

[24] Liu L., Guan M., Zhang X., Zhu Y., Lv H., Meng C. "Frequency information extraction based on time-frequency ridges for characterizing thin sand bodies," J. Geophys. Eng., vol. 19, no. 2, pp. 167-177, 2022, DOI: 10.1093/jge/gxac008.

[25] Oliveira P. M., Barroso V. "Instantaneous frequency of mono and multicomponent signals," Proc. IEEE-SP Int. Symp. Time-Frequency Time-Scale Anal., pp. 105-108, 1998.

[26] Kulia G., Lundheim L., Molinas M. "Tool for detecting waveform distortions in inverter-based microgrids: A validation study," 2016. DOI: 10.1109/GHTC.2016.7857330.

[27] Abdel-Galil T. K., El-Saadany E. F., Salama M. M. A. "Online tracking of voltage flicker utilizing energy operator and Hilbert transform," IEEE Trans. Power Deliv., 2004, DOI: 10.1109/TPWRD.2004.824428.

[28] Bernal D., Gunes B. "An examination of instantaneous frequency as a damage detection tool," Proc. 14th Eng. Mech. Conf., Austin, …, pp. 2-7, 2000.