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IDENTIFICATION OF PROGRESSIVE DAMAGE IN STRUCTURES USING TIME-FREQUENCY ANALYSIS

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Abstract: Efficient diagnosis and prognosis of civil infrastructure require a real-time assessment of its progressive damage over time under in-service conditions. Wavelet transform (WT) is one of the powerful signal processing tools that can decompose a signal into a summation of time-domain functions at various frequency resolutions. The simultaneous time-frequency decomposition capability of WT provides a unique advantage over the traditional Fourier transform in analyzing nonstationary signals. One drawback of the WT is that its resolution is rather weak in the high-frequency region. Since structural damage is typically, a local phenomenon captured most likely by high-frequency modes, the potential drawback of WT can affect its application towards damage identification. Additionally, most of the studies are restricted to the identification of discrete damage only, and there has been limited research on progressive damage. The goal of this paper is to develop a robust damage detection algorithm capable of capturing damage progression using vibration data collected through various sensors. In this paper, synchrosqueezing transform (SST) is used for progressive damage assessment in the structures with the aid of changes in modal parameters. The results are validated using various numerical simulations.

1 INTRODUCTION

Most of the existing infrastructure in North America was built in the post-World War II era. Many water and sewer treatment facilities, bridges, dams, wind turbines, culverts or pipelines are close to the end of their remaining useful life due to aging, growing populations and exponentially increasing the operational load, extreme weather conditions, and natural disasters. The ability to continuously monitor the desired functionality and integrity of civil infrastructure facilitates potential solutions to reduce annualized maintenance cost while providing increased safety to the public. In the absence of adequate repair and maintenance, the progressive damage leads to the ultimate collapse of structures.

Structural Health Monitoring (SHM) is an emerging and powerful diagnostic tool for damage detection and disaster mitigation of structures. Structural damage identification, one of the important components of SHM, is critical for confirming the satisfactory performance of the infrastructure. The assessment of progressive damage requires a tool that can mathematically evaluate and graphically represent the continuous damage in the structures (Reynders 2012). In fact, time-frequency analysis methods are apt for understanding the damage in the structure as they show a variation of the modal parameters in both time and frequency domain. The time-frequency analysis methods and wavelet transforms (Hou et al. 2000) in particular have been improved in the last decade; blind source separation (BSS) (Sadhu et al. 2017), EMD (Huang et al. 1998) and SST (Daubechies et al. 2010) being the recent method with robust mathematical foundation. However, conventional time-frequency analysis techniques suffer from a trade-off between time resolution and frequency resolution. A reliable condition monitoring of structures can be performed by analyzing it in the spatiotemporal state while acquiring an impartial knowledge of both time and frequency parameters.

Synchrosqueezing transform (SST) has been recently developed as an improvement to a continuous wavelet transform with an enhanced time-frequency representation. This mathematical formulation of SST was presented in (Thakur 2015) explaining the theoretical aspects of the synchrosqueezing transform and its stability properties. SST combines the localization and sparsity properties of time-frequency representation with the invertibility of conventional time-frequency transform. It is also a robust method for signals involving noise. Another theoretical study (Yang 2018) evaluated the statistical properties of SST for better representation and manipulation under measurement noise. Mihalec et al. (Mihalec et al. 2016) explored damping identification using CWT and SST; it was shown that SST lacks in differentiating between closely spaced frequencies. The modification to generalized SST was proposed to deal with a beating by designing constant frequency of oscillation and time-wise averaging of the reallocation criterion. The discrete SST was used for modal identification of high-rise structures. The natural frequencies and damping ratio of in-service structures were obtained using the proposed method showing its applicability in condition monitoring of the structures (Li and Park 2017).

In (Herrera et al. 2018), the time-varying signal analysis using continuous wavelet and synchrosqueezing transform was studied using four different signals with a wide range of frequency characteristics. The study (Kumar et al. 2017) evaluated the applicability of various time-frequency techniques for damage detection in structures using frequency shifting. It was shown that SST outperforms other techniques in the representation of the frequency shifts as the frequency component is squeezed and localized over time. In (Sanchez-A et al. 2015), a novel idea of detecting, locating and quantifying the damage severity in the high-rise structures was undertaken. They used SST and nonlinear-dynamics based fractality dimension for identifying and locating the damage in the structures. A damage index was proposed for presenting the severity of the damage. However, identification and isolation of progressive damage is still an unexplored area. In this paper, SST is explored as a possible tool for identifying progressive damage in the structure. The paper is outlined as follows. First, a brief introduction of the SST method is presented followed by a depiction of its capability in signal decomposition and frequency tracking. Numerical simulations are conducted next followed by the key conclusions of the proposed research.

2 SYNCHROSQUEEZING TRANSFORM

2.1 Mathematical background

Time-frequency analysis allows representing spatiotemporal information for a signal. The majority of time-frequency analysis algorithms fall under linear or quadratic methods. However, with few setbacks due to lack of interpretation or reconstruction of signals in case of quadratic methods, advancements are always seeking to improve the time-frequency representation. A general SST is an adaptive and invertible transform developed to improve the quality or readability of the wavelet-based time-frequency representation by squeezing it along the frequency axis (Daubechies et al. 2010)). It aims to sharpen a time-frequency representation by allocating its value to a different point in the time-frequency plane determined by the local behavior. The SST uses these steps (Daubechies et al. 2010):

1. Obtain the continuous wavelet transform (CWT) of the input signal. The CWT must be an analytical wavelet to capture instantaneous frequency information.
2. Extract the instantaneous frequencies from the CWT output, W_f, using a phase transform, ω_f. This phase transform is proportional to the first derivative of the CWT with respect to the translation, u. In this definition of the phase transform, s is the scale.

$$[1]\ \omega_f(s,u) = \frac{\partial t W_f(s,u)}{2\pi i W_f(s,u)}$$

The scales are defined as $s = \frac{f_x}{f}$, where f_x is peak frequency and f is the frequency.

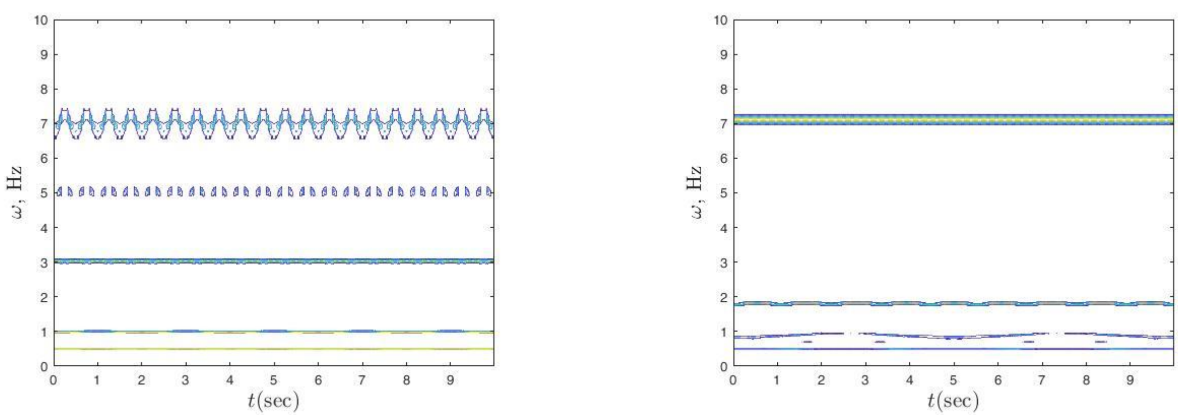
3. "Squeeze" the CWT over regions where the phase transform is constant. The resulting instantaneous frequency value is reassigned to a single value at the centroid of the CWT time-frequency region. The reassignment results in a sharpened output from the SST when compared to the CWT.

The improvement to signal representation has allowed the exploration of this method for understanding progressive damage in structures. The applicability of SST is explored in this paper to understand its use in detecting progressive damage in structures through numerical studies. The numerical study is performed on one (SDOF) and four degrees (4-DOF) of freedom model.

2.2 Signal decomposition

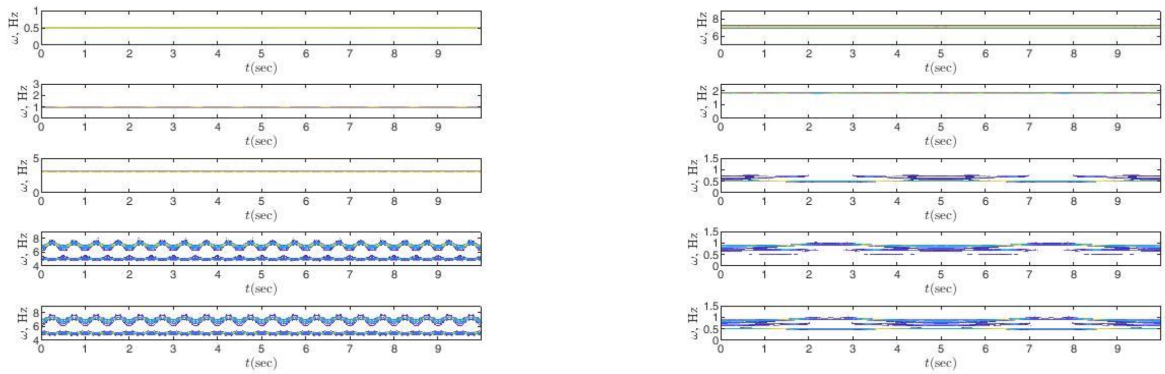
Two signals are used to evaluate SST's performance under well separated and closely spaced frequencies. The frequencies, 0.5 Hz, 1.0 Hz, 3.0 Hz, 5.0 Hz, and 7.0 Hz are used for well-separated case and frequencies, 0.5 Hz, 0.7 Hz, 0.9 Hz, 1.8 Hz, and 7.0 Hz are used for the closely spaced example. A sampling frequency of 100 Hz and a total duration of 10 seconds is used for the simulation.

In figure 1, the SST response of mixed signals is shown, and the corresponding reconstructed individual signals are shown in Figure 2. It can be observed that for well-separated frequencies, all the individual signals are reconstructed and distinguishable with some mode mixing for higher frequencies. However, for closely spaced frequencies, 'beating' occurs and closely spaced frequencies are not distinguishable at 0.7 Hz and 0.9 Hz. This can be treated as one of the drawbacks of the SST method.



(a) (b)

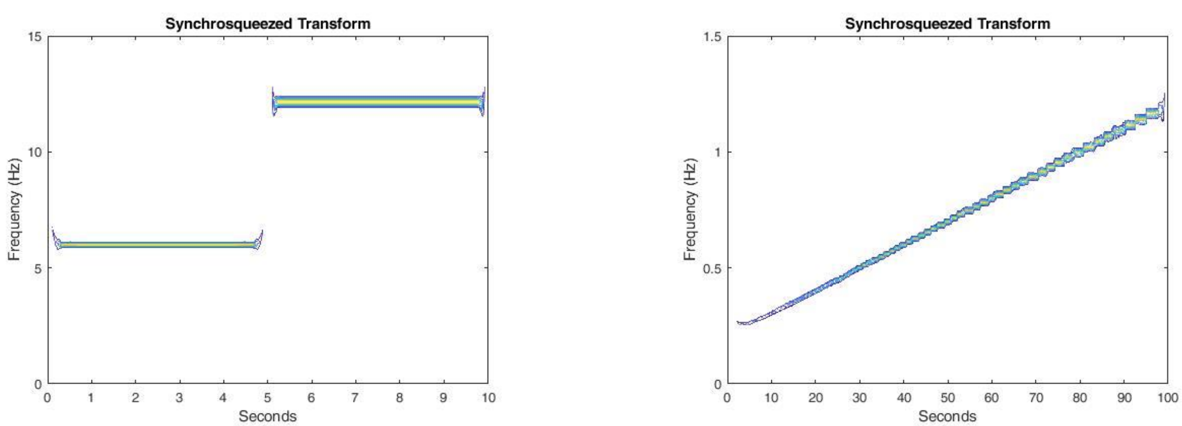
Figure 1. The SST of signals containing (a) well-separated (b) closely-spaced frequencies



(a) (b)

Figure 2. The reconstructed signal of mixed signals containing (a) well-separated (b) closely-spaced frequencies

Figure 3(a) shows the SST response of a sine signal that undergoes an instantaneous change in the frequency from 6 Hz to 12 Hz at t=5 seconds. Figure 3(b) shows the SST response of sine sweep signal where the frequency changes between 0.25 Hz to 1.25 Hz over 100 seconds with 20% measurement noise. It is evident from the results that SST can track the change in the signal which will be apt for quantifying progressive damage in structures.



(a) (b)

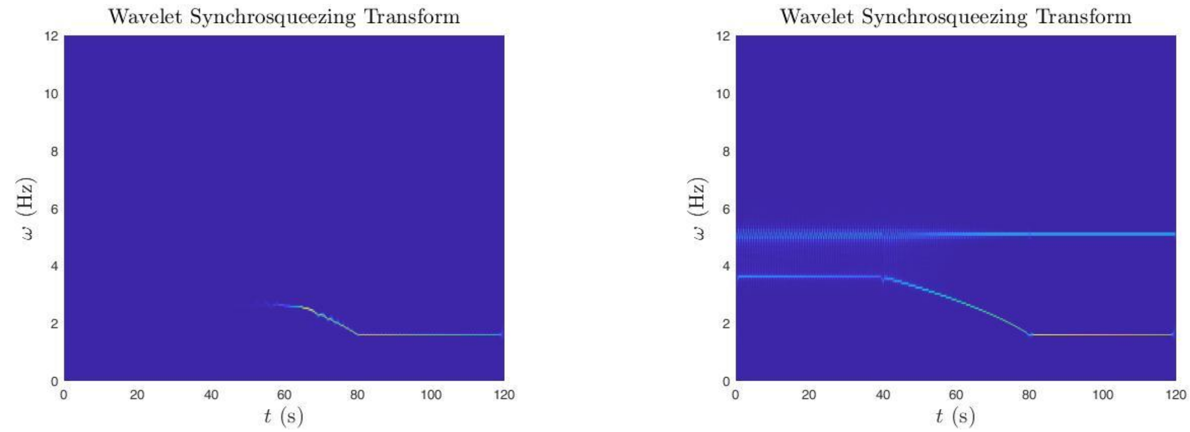
Figure 3. The SST response of (a) Sine signal with frequency discretely changing from 12 Hz 6 Hz, (b) Chirp signal with frequency changing from 0.25 to 1.25 over 100 seconds.

3. NUMERICAL STUDIES

3.1 SDOF model

A single DOF system is first selected to test the performance of the SST. A 10 kg lumped-mass model with a progressive stiffness reduction from 5000 to 1000 N/m between 20-30 seconds is used for the illustration.

The model has an undamaged and damaged natural frequency of 3.6 Hz and 1.6 Hz, respectively. The performance of the SST using the vibration response of the SDOF model subjected to a harmonic frequency of 2.6 Hz and 5 Hz are shown in Figure 4, respectively. In Figure 4(a), an increase in amplitude can be seen since the system's natural frequency matches with the forcing frequency (i.e., 2.6 Hz) at 65 seconds. Whereas, Figure 4(b) shows a separate frequency of 5 Hz along with accurately tracking of progressive changes of natural frequencies. Therefore, the SST provides a better picture of what is happening to the system than any other frequency or time-domain methods.



(a) (b)

Figure 4. The SST response of SDOF subjected to harmonic excitation with a frequency of (a) 2.6 Hz and (b) 5 Hz.

3.2 4-DOF model

In this section, a 4-DOF model is used to test the damage performance of SST. Two different damage scenarios are conducted to check the sensitivity and accuracy of the proposed method. For example, Case 1 (C1) represents 50% damage on the first floor and no other damages in the subsequent floors. Case 2 (C2) represents 30% damage on all floors. All the damages are simulated through a linear stiffness reduction between 20th and 30th seconds. In this section, a 4-DOF model is used as shown in Figure 5. A consistent stiffness and damping of 200 N/m and 1.05 N. s/m, respectively are used for all the floors. The floor masses for m_1, m_2, m_3 is 5.0 kg and m_4 = 10 kg. The damage scenarios considered for this study are listed in Table 1. The theoretical frequencies for damaged and undamaged cases are shown in Table 2. The percentage frequency change alongside the natural damaged frequency is also shown for every case and mode. For example, C1 with 50% damage in the first floor as shown in Table 1 results in 13.4%, 6.1%, 3.9%, and 1.1% reduction in modal frequencies as shown in Table 2. The percentage change is shown in parenthesis.

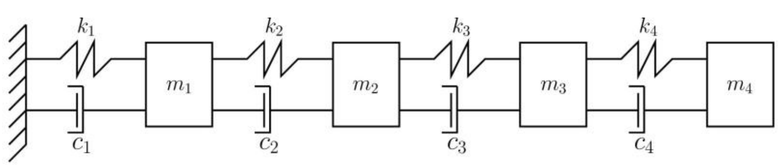


Figure 5. 4DOF Model

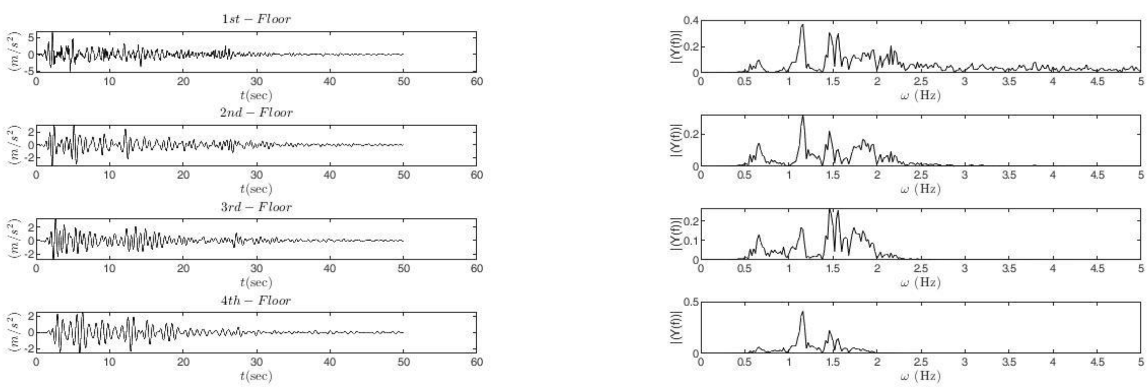
Table 1. Damage scenarios

Damage cases	1st Floor	2nd Floor	3rd Floor	4th Floor
C1	50%	0	0	0
C2	30%	30%	30%	30%

Table 2. Change of frequencies (in Hz) under different damage scenarios

Undamaged	0.67	1.14	1.53	1.88
C1	0.58 (13.4%)	1.07(6.1%)	1.47(3.9%)	1.86(1.1%)
C2	0.56(16.4%)	0.95(16.6%)	1.28(16.3%)	1.68(10.6%)

Figure 6 shows the floor vibration data and the corresponding Fourier spectra of the data. SST is performed on the acceleration data, and first two modes with higher energies were extracted, reconstructed, and SST was again performed on them to observe different progressive damage modes as shown in Figure 7 and Figure 8 for C1and C2, respectively.



(a) (b)

Figure 6. (a) Vibration measurement (b) Fourier spectra

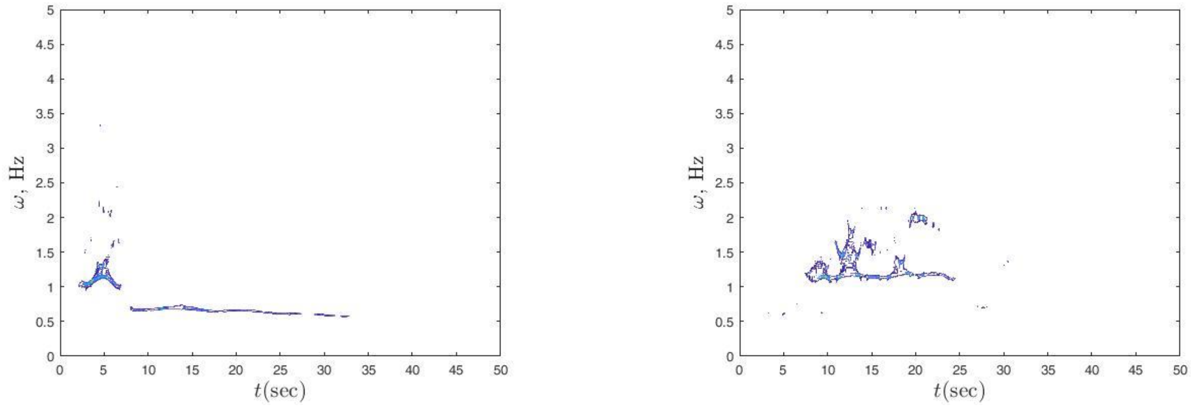


Figure 7. The progressive decrement in frequency for various modes between 20th and 30th second for C1.

It can be observed from Figure 7; the frequencies minutely change from their undamaged value to damaged value between the above-mentioned time duration. For example, it clearly shows the change in the first frequency from 0.67 Hz to 0.58 Hz. Similarly, for C2, the progressive damage as represented by a change in frequencies (from 0.67 Hz to 0.56 Hz) over 20th and the 30th second is shown in Figure 8.

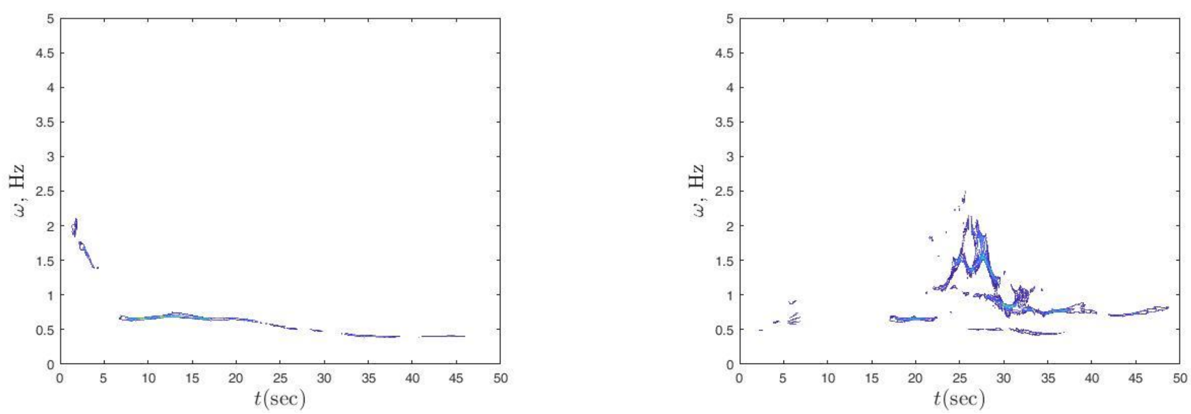


Figure 8. The progressive decrement in frequency for various modes between 20th and 30th second for C2.

4. Conclusions

An attempt is made to harness the robustness of the SST for modal decomposition and its capability to identify progressive damage in the structures. The method is validated by simulating a suite of numerical models. The poor performance of SST in identifying closely spaced modes creates a gap that requires further evaluation and improvement in the SST method. A few signals show mode mixing while reconstructing signals obtained from the well-separated frequencies. The progressive tracking of the frequency's capability of SST and its clear representation show its potential for progressive damage analysis for structures. However, mode mixing while reconstruction and beating phenomena require further evaluation for the efficient application to real-life structures.

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