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On the use of Stockwell transform in structural dynamic analysis

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Abstract. Time-frequency analysis of earthquake records using Fourier transform is a fundamental, reliable and useful tool in earthquake engineering and engineering seismology. It will be however no longer functional if the frequency variation is analysed in time domain. Short time Fourier transform is utilized for the same purpose but this has also its own limitations and restrictions. In this research, Stockwell transform (S-transform), is evaluated in investigating frequency content of signal in time domain. First, the effectiveness of S-transform was tested by a non-stationary synthetic signal series with a sum of various instantaneous time varying frequency functions. Then, transform was employed to three different earthquake waveforms of Iwate-Miyagi Nairiku earthquake (M_W 6.9, 2008); recorded in near, moderate and far sites. Finally, an application was demonstrated for determining dynamic response of three-story frame structure by using El Centro earthquake compiled with harmonic motion. Unlike widely used continuous wavelet transform, which provides temporal and spectral information simultaneously, S-transform is very straightforward and easy to manipulate for interpretations. All cases considered in this research showed that S-transform can be implemented for further research activities related with frequency-dependent strong motion analysis by practitioners and engineers. S-transform can distinguish abrupt frequency changes in structures effectively and accurately.

Keywords. Time-frequency domain; Stockwell transform; structural dynamic analysis; near-far field earthquake ground motion.

1. Introduction

Two independent domains, frequency and time, are essential to analyse and to evaluate the earthquake records in order to get better understanding of earthquake source, path and site effect. They are also used to assess the damages in structures (Motosaka *et al* 2008). Records with perfect time resolution and the magnitude of the Fourier transform (FT) of the signal with perfect spectral resolution are inadequate to understand the variation of frequency in time throughout the signal history (Kuyuk & Kuyuk 2010; Kuyuk *et al* 2011). Time dependent parameters such as peak ground acceleration (PGA), peak ground velocity (PGV) and peak ground displacement (PGD) are mostly do not correspond directly (or with large standard deviation) to the damage degree of structures (Mucciarelli *et al* 2004; Elenas 2000; Wu *et al* 2004). Therefore, time-frequency representation of earthquake waveform is needed for signals containing multiple time varying frequencies (Todorovska 2001). The structural damage is dependent on time-duration of the earthquake as well as on amplitude and frequency content of waves whereas Fourier amplitude spectra (FAS) neglects the time-duration of dominant frequency of strong ground motion. However, time-duration of dominant frequency of strong motion can be identified with Short Time Fourier Transforms (STFT), wavelet, Hilbert and Stockwell transform (Kuyuk *et al* 2010; Mansinha *et al* 1997; Nagarajaiah & Basu 2009).

Wavelet transform has undertaken fast theoretical and application-oriented development in the last two decades, as its effectiveness for a range of problems. There are extensive works available regarding the features of the approach as well as the algorithmic details in literature (Mallat 1999). Contrary to Fourier analysis which represents a signal using a linear combination of sine waves, (each representing a signal of infinite length and a single frequency), wavelet transform decomposes a signal into wavelets that are confined in time and that represent a particular range of frequencies. Representing the signal as wavelets rather than a summation of stationary sine waves is preferable for non-stationary signals such as earthquake ground motions (Baker 2007). The S-transform is one of time-frequency representations that is similar to wavelet but known for its local spectral phase properties. It combines a frequency dependent resolution of the time-frequency space with the precise referenced local phase information. User can define the phase in a local spectrum setting and this results many advantageous characteristics for representing time and frequency at the same time (Stockwell *et al* 2007).

Duration of an earthquake is a frequency-dependent quantity because of frequency-dependent attenuation and the complexity of the earthquake rupture. Montejo & Kowalsky (2008) investigated the relation of frequency-dependent strong motion duration using wavelets and its influence on nonlinear seismic response. Their proposed procedure includes decomposing the record into constituent functions with dominant frequencies within a limited (pre-defined) range via a continuous wavelet transform. (Basokur *et al* 2003) examined the time-frequency representation of strong ground motion records for damage appraisal after Duzce earthquake by using S-transform. Applicability of S-transform to structural vibration or to structural health monitoring has not been yet investigated to track frequency changes in real-time.

In this study, S-transform is used to identify attenuation effect of Iwate-Miyagi Nairiku earthquake and its application is demonstrated for the nonlinear response of three-story frame structure for the purpose of structure health monitoring. First, the effectiveness of S-transform is tested by a non-stationary synthetic signal series with a sum of various time varying frequency functions. Second, three earthquake ground motions recorded in MYG005, FKS005 and CHB019 stations on Kyoshin Network, Japan are selected to calculate the dynamic characteristics of ground motion considering near-fault and far-site effect. Finally, frequency changes of the structures in time domain is analysed under El Centro earthquake record with various sinusoidal harmonic motions. It is verified that S-transform can capture variation of instantaneous frequency directly and is computationally inexpensive.

2. Methodology

Before development of wavelet transform, STFT has been used to analyse the localized variations of frequency content in time domain. The basic idea of STFT is that to analyse the frequency content of the signal at a particular interval time. Performing the FFT on the whole signal, result in no information about frequency variations as seen Eq. 1. (figure 1b).

$$S(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} s(t) e^{-i\omega t} dt, \tag{1}$$

here $S(\omega)$ and $s(t)$ are the FT pairs, ω and t are frequency and time.

On the other hand, the STFT (figure 1c) is based on fixed resolution depends on time window as;

$$STFT(t,\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} s(t) w(\tau - t) e^{-i\omega t} d\tau, \tag{2}$$

where τ is the running time in which $w(\tau - t)$ is a window function of $\tau - t$ that emphasizes the signal around the time t. This windowing function determines the resolution where narrow window results in good time resolution but poor frequency resolution and vice versa. The spectrogram (or the energy density of the modified signal) is given by,

$$SP_{STFT}(t,\omega) = |STFT(t,\omega)|^2 . \tag{3}$$

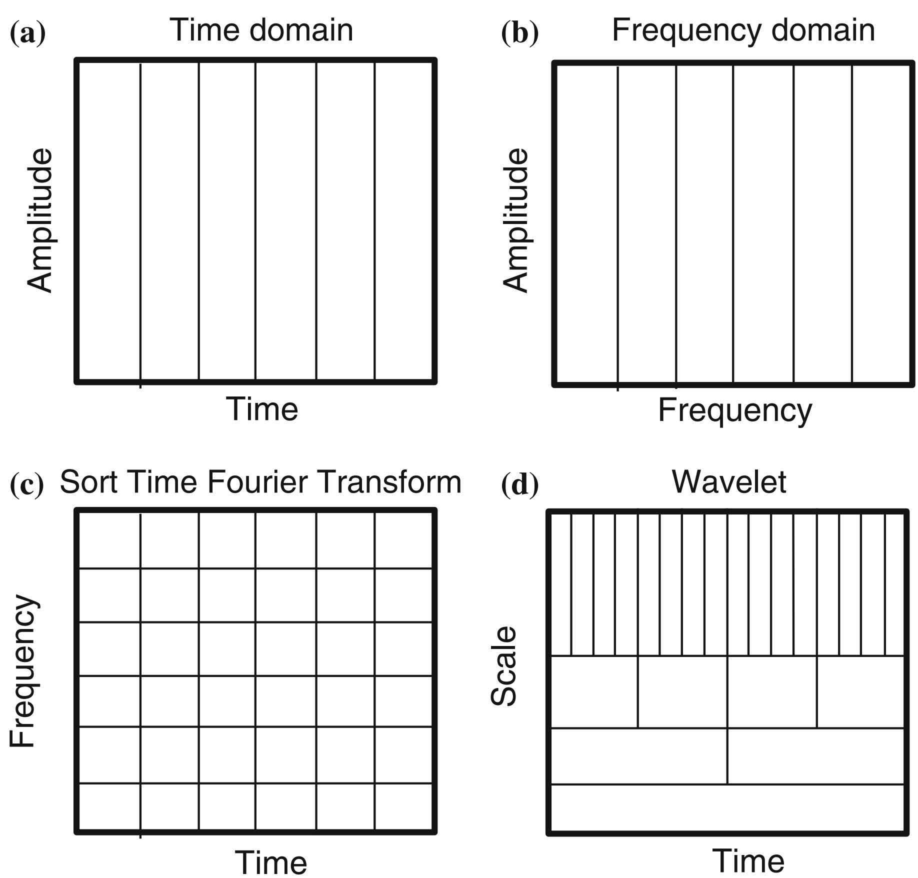

Figure 1. Comparison of **(a)** time domain, **(b)** frequency domain, **(c)** sort time Fourier transform and **(d)** wavelet transform.

The fixed resolution is the main restraint of STFT. This problem was overcome by multi-resolution analysis using wavelet. Indeed, the wavelet convolves the signal with a function that varies in both time and frequency like STFT however its window boundaries are not in constant shape (figure 1d). Better frequency resolution is obtained in lower frequencies since sub-windows are fatter whereas better time resolution is obtained in high frequencies due to slim sub-windows. This time–frequency representation provides unique information of strong ground motion such as variation of frequencies in time.

The continuous wavelet transform (CWT) can be defined as the correlation of a signal $s(t)$ with translations (b) and dilations (a) of a wavelet $\psi(t)$ as

$$W_{\psi}(b, a) = \int_{-\infty}^{\infty} s(t) \frac{1}{\sqrt{a}} \overline{\psi} \left(\frac{t-b}{a} \right) dt, \tag{4}$$

where $\overline{\psi}$ is the complex conjugate of $\psi(t)$. In this study, a special case of CWT using Morlet-type mother wavelet, called S-transform, with frequency identified as inverse scale and a phase and amplitude adjustments is used. S-transform and wavelet transforms satisfy the above relationship

$$ST(b, \omega) = \sqrt{|\omega|} e^{-2\pi i b \omega} W(b, 1/\omega), \tag{5}$$

where ST is the Stockwell transform. The conversion of scale to frequency $(a \rightarrow 1/\omega)$ and a frequency-dependent scaling of amplitudes is advantageous in many applications which gives clear interpretation of frequency for practitioners (Gibson *et al* 2006). The mother wavelet is the modulated Gaussian also known as a complex Morlet wavelet (Daubechies 1992) defined as

$$\psi(t) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}t^2} e^{2\pi i t}. \tag{6}$$

Therefore Stockwell transform can be derived as

$$ST(b, \omega) = \int_{-\infty}^{\infty} s(t) \frac{|\omega|}{\sqrt{2\pi}} e^{-\frac{(t-b)^2 \omega^2}{2}} e^{-2\pi i \omega} dt \tag{7}$$

or since transform is complex, it can be written as

$$ST(\tau, \omega) = A(\tau, \omega) e^{i\varphi(\tau, \omega)}, \tag{8}$$

where $A(\tau, \omega)$ is the amplitude of S-spectrum and $\phi(\tau, \omega)$ is the phase of spectrum.

The algorithm described above was implemented in the Matlab software by Stockwell *et al* (1996). The current algorithm requires less than 5 seconds on a desktop computer to analyse a ground motion consisting of 10000 data points. Even though computational time of the procedure seems not a major problem for a small amount of waveform data, it is however beneficiary for a huge number of records in seismology along with the recent big data studies in geophysics, astronomy and cloud computing.

3. Results

S-transform is tested for three cases, artificial synthetic signal, earthquake ground motion, and structural health monitoring, to prove its effectiveness for various conditions.

CASE I: Application in artificial synthetic signal series

Earthquake ground motions are non-stationary in amplitudes with the accumulation of energy at the beginning and decay at the end. They are also non-stationary in frequency due to arrival of dissimilar seismic waves at different time-instants and phenomenon of attenuation, dispersion, scattering and diffraction. Therefore, the effectiveness of S-transform is tested by a non-stationary synthetic signal series constructed with sum of various instantaneous time varying frequency functions (figure 2). Artificial signal contains 8 sub-signals with frequencies shown in Eq (9)

$$y(t) = \begin{cases} 0.1\, rand(t) & 0\,s < t \leq 4\,s \\ 0.5\, rand(t) & 4\,s < t \leq 8\,s \\ rand\ (t) & 8\,s < t \leq 12\,s \\ \sin\ (0.5t) & 12\,s < t \leq 16\,s \\ \sin\ (1.5t) & 16\,s < t \leq 18\,s \\ \sin\ (5t) & 18\,s < t \leq 20\,s \\ \cos\ (f_p(t)t) & 20\,s < t \leq 24\,s \\ \cos\ (f_q(t)t) & 24\,s < t \leq 28\,s \end{cases}, \tag{9}$$

where 'rand' represents noise and $f_p(t)$, $f_q(t)$ are instantaneous frequency sweeps in which former changes 5 to 0.05 Hz and latter changes 0.05 to 5 Hz. In the first part of the artificial signal, three white noises with different amplitudes (0.1, 0.5 and 1.0) are introduced between 0 and 12 s. Next part contains sine signals which has one constant frequency in time (0.5, 1.5 and 5 Hz) until 20 s. In the last part, swept-frequency cosine (chirp) signals are presented.

Fourier amplitude spectrum of signal is shown figure 2c in logarithmic scale. The frequencies of sine waves, 0.5, 1.5 and 5 Hz, are seen with a dominant value of 0.5 Hz. This is due to the duration of 0.5 Hz, which is twice as much as the others. The contribution of cosine signals between 0.05 Hz and 5 Hz amplified the Fourier amplitudes in this range. The noise is also seen in the later portion of 10 Hz. However, it is impossible to see local frequency variations by looking at FT only. S-transform of signal is shown in figure 2b. Abrupt changes in the frequency are seen where light colours indicate the amplitude of the frequency range. Sinus with 0.5 Hz frequency occurred in 12–16 s, 1.5 Hz and 5 Hz comes after with 2 s intervals are distinguishable. Also, the decrease and increase in frequencies correlate with the bands seen in 20–28 s.

The effect of the amplitude in signal can be evaluated by investigating spectrum of noises. S-transform does not indicate any particular frequency in the noise portions of synthetic signal.

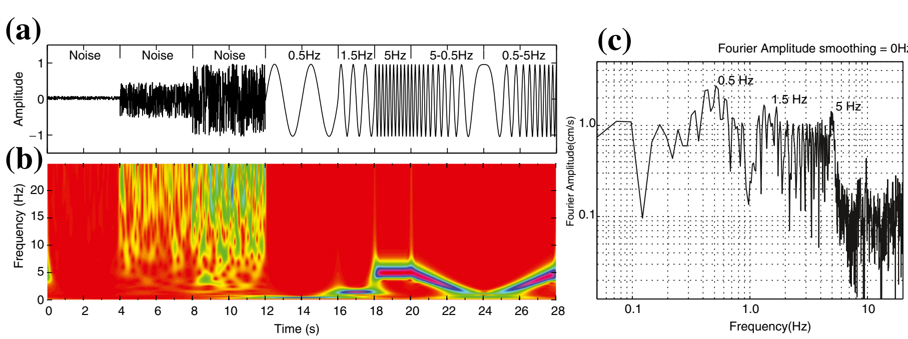

Figure 2. **(a)** An artificial non-stationary synthetic signal series with a sum of various instantaneous time varying frequency functions containing sine, cosine and random signals. **(b)** S-transform, **(c)** Fourier amplitude spectra of synthetic signal.

Instead a wide frequency band, the mixture of random texture is seen. However, the amplitude value of one is darker (green) than the amplitude value of 0.5. There is almost no texture in the 0.1 Hz part of noise. Red contour implies low level of amplitude in signal.

CASE II: Application in earthquake ground motion

In order to analyse the performance of S-transform in recorded accelerations, three signals were investigated in three locations from Iwate-Miyagi Nairiku earthquake occurred on 14th June 2008 with M_{JMA} 7.2 (figure 3). The epicenter was located at 39° 01.7N – 140° 52.8E. The strongest tremours measured in the cities of Ōshū (Iwate) and Kurihara (Miyagi), were "strong 6" out

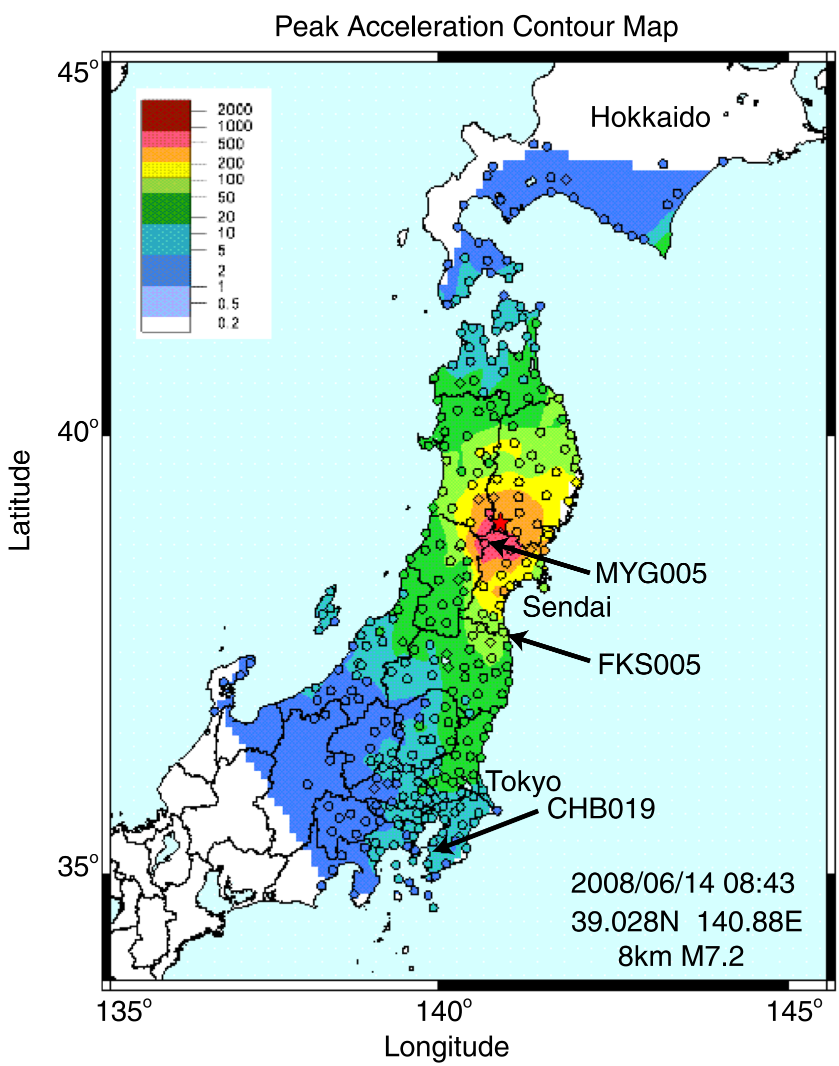

Figure 3. Peak ground acceleration contour map of Iwate-Miyagi Nairiku earthquake June 14, 2008, (with Mjma 7.2). Arrows show the location of sites. MYG005, FKS005, CHB019 stations are analysed in this study (map changed from http://www.k-net.bosai.go.jp/).

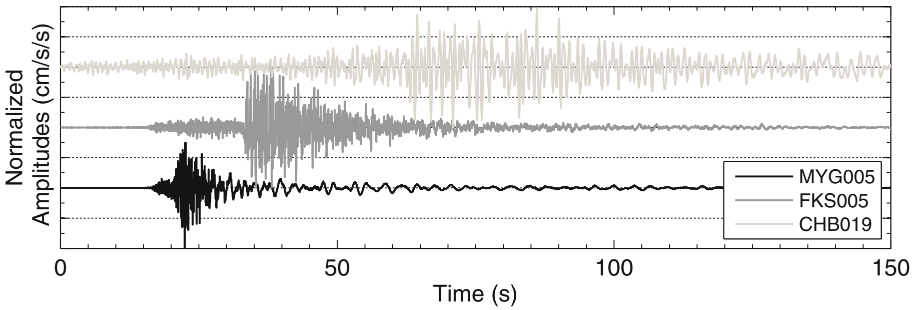

Figure 4. Normilized acceleration ground motion (EW component) recorded at MYG005, FKS005 and CHB019 stations located 32, 154 and 444 km far from the epicenter with a max 521.3, 44.2 and 5.2 gal.

of 7 on seismic intensity scale of JMA. Total of 329 stations in Kyoshin Network (K-NET) recorded the earthquake from near to far epicenteral distances. K-NET is nationwide strong-motion seismograph network with 1,000 observatories deployed all over Japan. Near (MYG005), moderate (FKS005) and far (CHB019) sites have different signal components as high frequency content decreases with the distance. Figure 4 shows the normalized, non-filtered EW component of the signals of the earthquake. Peak ground accelerations (PGA), JMA intensities, locations of stations, epicentral distances are given in table 1.

Fourier amplitudes of records, which are smoothened with 0.1 Hz Parzen filter, are shown in figure 5a (Parzen 1962). Fundamental frequencies are 0.65 Hz, 1.8 Hz and 1 Hz for waveforms of MYG005, FKS005 and CHB019 stations, respectively. High frequency content of signals decreased with distance. Long period motion is dominant for the record obtained from CHB019 whereas the dominant frequency band is wider for the records obtained from FKS019 station. Same conclusions can be reached by examining normalized linear acceleration response spectra of records with 5% critical damping ratio (figure 5b). Peak values are shifted into the long periods.

Figure 6a is the S-transform of acceleration record at MYG005 station. High frequency is clear between 15 s–35 s, for which P and S waves are effective. Because this station is very close to the epicenter, P and S waves are not separated for this part of the record. High frequency content diminished after 35 s. However, the dominant frequency with a value of 0.65 Hz. is visible until the end of the record. This is one advantage of wavelet analysis since wider cells representing low frequencies are well-defined in the plot (figure 1d). S-transform of EW component of acceleration recorded at FKS005 stations is shown in figure 6b. Due to epicentral distance (154 km) distinction between P- and S- wave is clear. P wave starts with higher frequency content of 7–15 Hz at 15 seconds. From introduction of S-wave to end of coda-waves, frequency band is very wide. This fact is also shown in FAS. S-transform of far field ground motion with a 5.2 cm/s^2 PGA recorded at CHB019 station is presented in figure 6c. High frequency has diminished as in

Table 1. Parameters of recorded signals in three sites.

Station codes	Peak acceleration (cm/s/s)	JMA Seismic intensity (max. 7)	P picking (s)	Latitude	Longitude	Epicentral distance (km)
MYG005	−521.3	5.5	15.15	38.80	140.65	32
FKS005	44.2	3.7	15.92	37.64	140.98	154
CHB019	−5.2	2.7	5.63	35.11	139.84	444

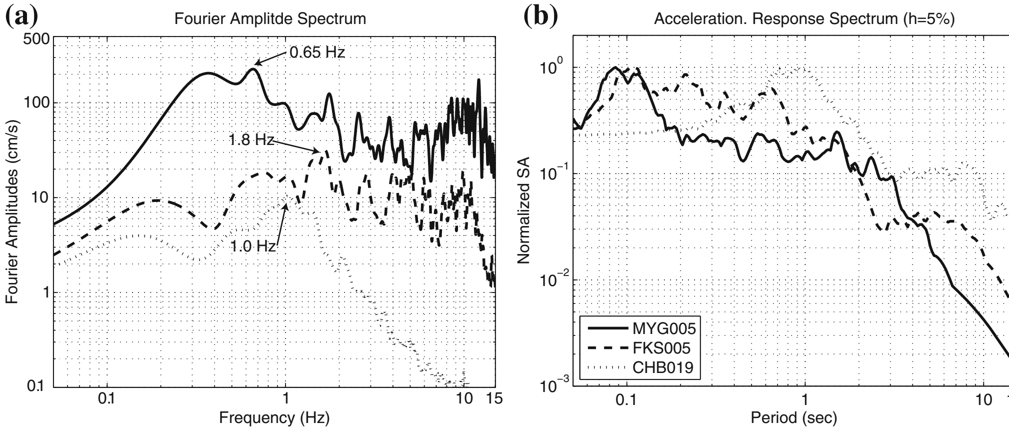

Figure 5. **(a)** Fourier amplitude spectra of MYG005, FKS005 and CHB019 stations. **(b)** Normalized acceleration elastic response spectra for 5% critical damping ration of three stations.

FAS (figure 5a). Fundamental frequency with a value of 1 Hz is observed throughout the signal history. Since the effect of S-wave initiation starts at 65 seconds the amplitude values are more significant between 60 and 100 seconds.

CASE III: Application to structural dynamic analysis

Conventional frequency analysis using Fourier Transform is insufficient to capture frequency changes in structures. However; damage sensitivity of structures can be tracked by wavelet transform. With this application our aim is to evaluate and demonstrate the ability of S-transform for identifying frequency content of structural response obtained from finite element analysis. For this purpose, a single bay three-story steel frame structure (figure 7) is analysed with commercial finite element software package SAP2000. Each floor is subjected to 50 kN dead load and a mass source is assumed to be twice as the dead load.

Determining structural damping is one of the most important steps in FEM of structures under dynamic loading. Rayleigh damping, in which mass-proportional damping and stiffness proportional damping are combined together. With this approach not only mass but also stiffness of the structure is included in the analysis. In steel structures, Rayleigh damping can be assumed as 5% (Chopra 2007). Structure is constructed with frame elements supported with fixed boundary condition. Instead of using method of mode superposition, a direct-integration time history analysis in which equations are solved for the entire structure at each time step is employed. Time history of response acceleration at the top of the structure in X direction is obtained numerically from the analysis applying El Centro earthquake record.

The only way to validate the effectiveness of S-transform is to test it with controlled input data. Thus, we have introduced sinusoidal harmonic motion to El Centro earthquake record, which already includes non-stationary frequency characteristics. These existing non-stationary frequency of earthquake record can be identified with FFT but still the information about its duration is lacking. To overcome this shortcoming for tracking frequency changes of the structures in time domain, El Centro earthquake is applied with sinusoidal harmonic motion for the following three cases; (i) 0.5 Hz sine wave for 18 seconds (figure 8a1), (ii) 0.5 Hz and 3 Hz sine wave for 18 seconds (figure 8b1) and (iii) 3 Hz, 0.5 Hz and 2 Hz sine wave for 6 seconds consecutively (figure 8c1).

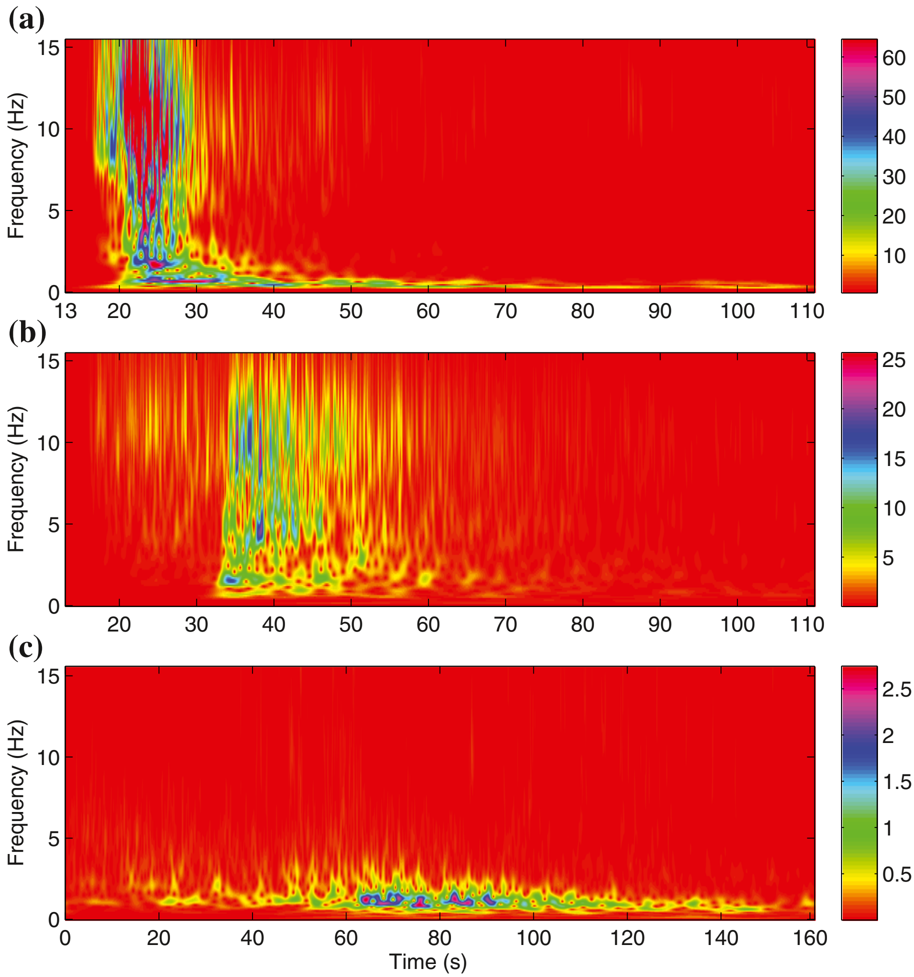

Figure 6. S-transform of acceleration record. **(a)** MYG005 station, **(b)** FKS005 station and **(c)** CHB019 station.

S-transform applied to the results that represent structure acceleration response for each three cases are shown in figure 8. Black solid lines plotted in all figures are either input or output time histories of the motion. The coloured maps are the results of the S-transform for the given motion. Sine wave with 0.5 Hz is apparent in output oscillation as in input motion for the first case (figure 8a1–a2). S-transform clearly highlights the fundamental frequency of the structure. Results from Fast Fourier Transform are also given next to results obtained from S-transform. S-transform is superior when compared to FFT because instantaneous frequency changes are tractable within time. Whereas FFT only shows the noise amplitude for full record history.

S-transform is ideal to determine high frequency content when 3 Hz harmonic motion is introduced. Together with 0.5 Hz, a non-stationary frequency of 3 Hz is also observed throughout the response (figures 8b1–b2). Lastly S-transform is tested with three different consecutive noises which are applied for a 6 seconds each (figure 8c1). With this test, it was aimed to understand

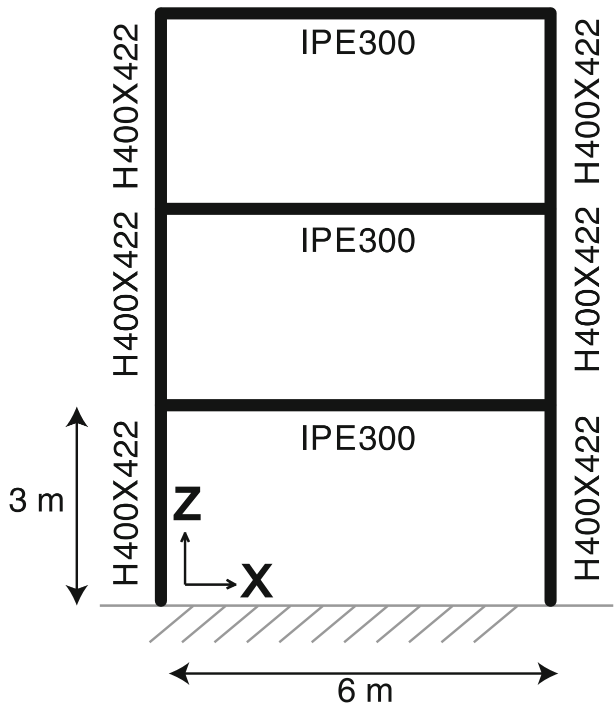

Figure 7. Geometrical and section properties of examined frame structure.

whether S-transform could pick abrupt frequency changes. S-transform achieved to discriminate each applied noise and dominant frequency of the structure as shown in figure 8c2.

4. Conclusions

Mapping of frequency content and spectral amplitudes of strong ground vibration is needed to understand the characteristic of vibration and the dynamic characteristic of structures. A wavelet based approach, S-transform, is discussed in this study for such need by presenting three different cases. Success of S-transform is also analysed with different input waves such as synthetic data, recorded near and far earthquake data and combination of artificial and real data. Results indicate that S-transform is able to recognize the variation of frequency for synthetic data in time domain. It is also very effective to evaluate non-stationary earthquake ground motion recorded in near–far field. However, S-transform is not helping in detecting high frequency band in observing non-stationary earthquake ground motion record due to the theory background of wavelet analysis in which narrow window is assigned for high frequencies. But, S- transform still can be a useful tool for structural dynamic analysis since most of the civil structure are not being affected by frequency higher than 7 Hz. Finally, S-transform makes it possible to provide temporal and spectral information simultaneously in structural dynamic analysis. With S-transform, designers can observe the frequency change and content in the response of structure. Thus, S-transform is user-friendly for interpretations, and it can be implemented for further research activities related to frequency-dependent strong motion analysis by practitioners and engineers.

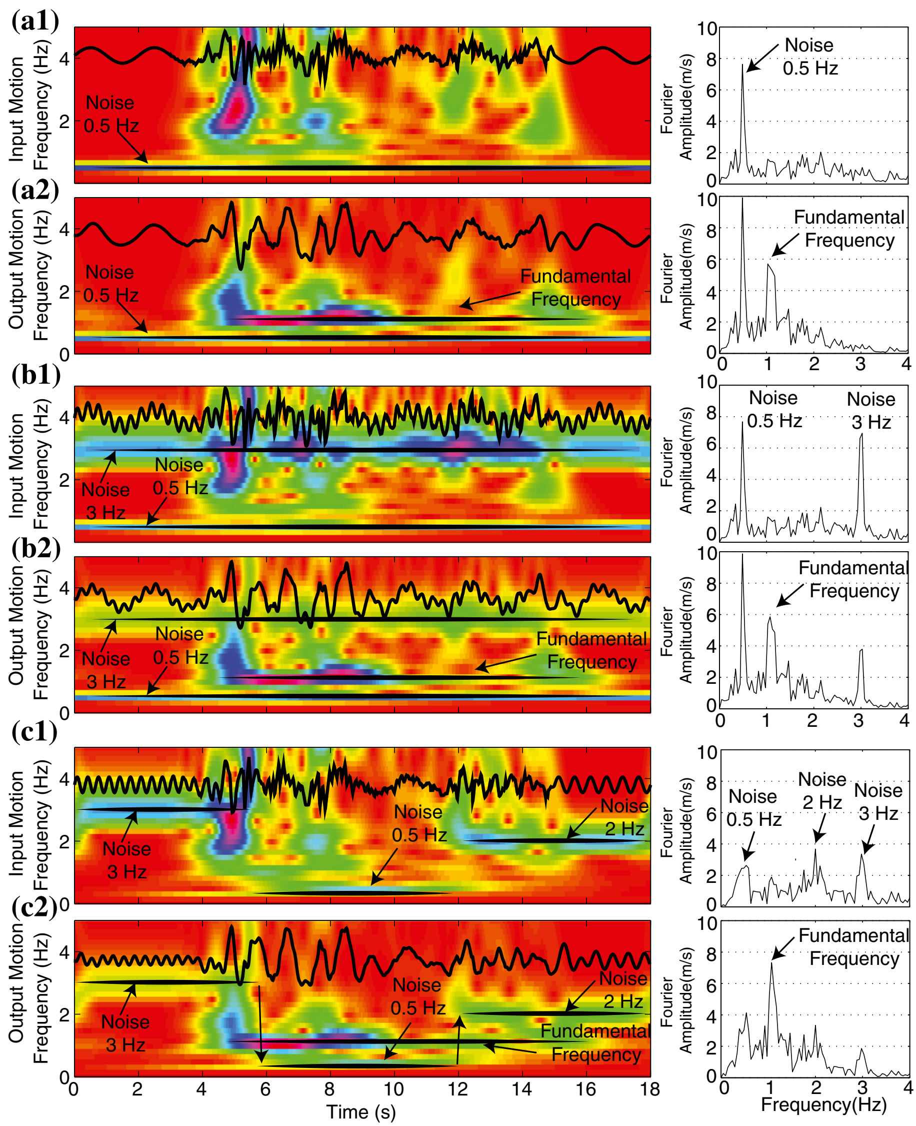

Figure 8. S-transform and FFT result for **(a1)** El Centro acceleration record with 0.5 Hz noise, **(a2)** response at the top of the structure, **(b1)** El Centro acceleration record with 0.5 Hz and 3 Hz noise, **(b2)** response at the top of the structure, **(c1)** El Centro acceleration record with 3 Hz, 0.5 Hz and 2 Hz noise applied 6 seconds consecutively and **(c2)** response at the top of the structure.

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