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Stockwell–Synchrosqueezing Transform based Spectral Decomposition for Ground Motion Signal Analysis

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ABSTRACT: Joint time-frequency representation technique is a good tool to analyze the ground motion signals having non-stationary properties. Some conventional techniques like STFT and Wavelet transform have limitations of t-f resolution. S-transform (ST) has superiority on STFT and WT as having good time localization. On the other hand Synchrosqueezing transform (SST) is a welldefined JTF technique. Continuous wavelet transform(CWT) based synchrosqueezing (SST) is developed by computing the CWT coefficients and then following the reassignment procedure. By considering the superiority of ST over CWT, Stockwell transform (ST) and Synchrosqueezing transform (SST) are carefully combined recently and called as Stockwell Synchrosqueezing transform (S-SST). The S-SST is introduced for the time-frequency analysis of ground motion signals. S-SST performance is demonstrated over ST and SST, by producing promising results on one synthetic signal and two real time ground motion signals of Uttarkashi earthquake (1991), in Himalayan Region, India. The better time and frequency localization are observed in the S-SST.

KEYWORDS—Ground motion signal, Synchrosqueezing transform, S-transform, Stockwell-synchrosqueezing transform, Time-frequency representation, Signal processing.

I. INTRODUCTION

Ground motion signals show non-stationary characteristics due to attenuation and absorption of seismic energy [1]. By evaluating the spectral variation properly and accurately many characteristics of these signals like any underlying periodicities may be detected [2]. A proper analysis of these signals help to study the response of different sites in occurrence of big earthquake, It becomes very much useful for Infrastructure development in seismically active areas, predicting earthquakes, and quantification of damage from the recorded motions.

Fourier transform is the most fundamental tool, which is used for the analysis of seismic signals, however, the time information of these signal cannot be obtained from the spectrum. For example, the same frequency vibrations at two different intervals present in the seismic signal are represented as single peak in the spectrum, the Fourier transform could not differentiate between the two. To circumvent this problem, joint time-frequency representations have been introduced which unfold the temporal information as well [3]. These transforms are able to map the time series into two dimensional quantity of time and frequency. Numerous methods have been proposed to extend the Fourier analysis to non-stationary signals and those are referred as T-F methods. The commonly used T-F representations employed in spectral decomposition of seismic signals are: Short Time Fourier Transform, Continuous Wavelet Transform, and Stockwell Transform. Using these linear transforms, the transformed spectral values may scatter over a strip in time-freq. plane whose geometry based on the window and signal [4]. This may lead to incorrect interpretation of spectral energies. These errors can be minimized by improving the time-frequency resolution [5]. Synchrosqueezing transform proposed in [6] has been applied for time-frequency analysis of seismic data [7]. Its application has been introduced to highlight individual components in seismic signals [8] and to find channels from a sedimentary basin [9]. A micro-seismic signal is separated into its individual constitutive phases and reconstructed as individual waveforms [10]. Inverse Q filtering is introduced to compensate the

attenuation of seismic waves using the synchrosqueezing transform (SST)[11].An Applications of synchrosqueezing transform has been introduced in attenuation estimation of seismic signal [12].

A detailed analysis of SST and other transforms with their comparison can be found in[13]. An application of synchrosqueezing transform based on CWT has been introduced to detect frequency shifting of earthquake damaged structure[3]. Hence, the challenge lies in choosing an appropriate time-frequency method for the analysis, because many time-frequency representations show limitations in terms of time and frequency localization. The leakage and frequency smearing are limitations in some recently developed T-F representations. Synchrosqueezing transform has a firm theoretical foundation and it even allows the reconstruction of non-stationary signal[14]. The S-transform offers better time resolution than the wavelet based transform and the lossless inverse transformation is also possible. It has the property of maintaining the original signal phase as well[15]. In the processing of ground motions, a good T-F resolution as well as proper time localization is needed to analyze the duration and frequency of most of the energy concentrations in a particular site where earthquake has occurred. Considering the superiority of S-transform over wavelet, Stockwell based synchrosqueezing which is referred as Stockwell synchrosqueezing transform (S-SST) was proposed in [5]. In this paper, this new time-frequency method is introduced. This transform improves the temporal resolution and spectral smearing so that it proves to be the better transform for spectral analysis of seismic signals.

II. PRINCIPLE

A. CWT Based Synchrosqueezing transform (SST)

The CWT of a signal $x(t)$ is represented as

$$W(a, \tau) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} x(t) \psi^* \left(\frac{t-\tau}{a} \right) dt \quad \text{-----(1)}$$

where ψ^* is complex conjugate of a mother wavelet, which is stretched by scale a and is shifted in time by τ . Equation (1) computes the CWT on uniformly sampled signal. The length variation of the mother wavelet permits a added flexible tradeoff among frequency and time localization, however, it does not stop spectral smearing in the Time - Frequency plane. This smearing occurs in the scale axis. To compute frequency variations with time, the instantaneous frequency should be computed in the wavelet domain. The derivatives of these wavelet coefficients ($W(a, \tau)$) are computed to estimate the instantaneous frequency [2]. So the instantaneous frequency $\omega_s(a, \tau)$ at point (a, τ) with regard to τ for all $W(a, \tau) \neq 0$ is

$$\omega(a, \tau) = \frac{-j}{2\pi W(a, \tau)} \frac{\partial W(a, \tau)}{\partial \tau} \quad \text{----(2)}$$

where $\omega(a, \tau)$ is the instantaneous frequency at each point (a, τ) on the spectrogram. To decrease the smearing, the frequencies are squeezed around the instantaneous frequencies which are ridges in the time-frequency representation. Each point of (a, τ) is changed to $(\omega(a, \tau), \tau)$. The $(W(a, \tau))$ coefficients are computed only at discrete scale values a_k , and $a_k - a_{k-1} = \Delta a_k$. As a third step, the values of t-f spectrogram is squeezed over a region where the phase transform CWT is constant. The resulting instantaneous frequency is reassigned, to a single value which is at the centroid of the CWT t-f region. The synchrosqueezing transform is calculated only at centers ω_l of the frequency range $\omega_l - \frac{\Delta\omega}{2}, \omega_l + \frac{\Delta\omega}{2}$ with $\Delta\omega = \omega_l - \omega_{l-1}$.

$$T_s(\omega_l, \tau) = \frac{1}{\Delta\omega} \sum_{a_k: |\omega_s(a_k, \tau) - \omega_l| \leq \Delta\omega/2} W(a_k, \tau) a_k^{-\frac{3}{2}} \Delta a_k \quad \text{---(3)}$$

here a_k which is the scale, is bounded by $|\omega_s(a_k, \tau) - \omega_l|$. To construct again the concentrated frequency map at time τ , a band of small frequency centered at ω_l and less than half of the bandwidth is used.



B. Stockwell-Synchrosqueezing transform (S-SST)

The Stockwell transform of a signal $x(t)$ is represented as

$$ST(f, \tau) = \frac{|f|}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} x(t) e^{\frac{-(t-\tau)^2 f^2}{2}} e^{-j2\pi f t} dt \quad \text{---(4)}$$

where f is the frequency; τ is the parameter that regulates Gaussian window's position on t-axis. Let

$$\psi(t) = \frac{1}{\sqrt{2\pi}} e^{-\frac{t^2}{2}} e^{j2\pi t} \quad \text{---(5)}$$

The Gaussian window time shifted by τ can be expressed as

$$\psi(t - \tau) = \frac{1}{\sqrt{2\pi}} e^{-\frac{(t-\tau)^2}{2}} e^{j2\pi(t-\tau)} \quad \text{---(6)}$$

The conjugate of the time shifted Gaussian window,

$$\psi^*(t - \tau) = \frac{1}{\sqrt{2\pi}} e^{-\frac{(t-\tau)^2}{2}} e^{-j2\pi(t-\tau)} \quad \text{---(7)}$$

The Gaussian window is scaled by frequency f ,

$$\begin{aligned} \psi^*[f(t - \tau)] &= \frac{1}{\sqrt{2\pi}} e^{-\frac{|f(t-\tau)|^2}{2}} e^{-j2\pi[f(t-\tau)]} \\ &= \frac{1}{\sqrt{2\pi}} e^{j2\pi f \tau} e^{-\frac{(t-\tau)^2 f^2}{2}} e^{-j2\pi f t} \quad \text{---(8)} \end{aligned}$$

The S-transform expression as in eq. (4) can be rewritten with eq. (8) as

$$ST(f, \tau) = |f| e^{-j2\pi f \tau} \int_{-\infty}^{+\infty} x(t) \psi^*[f(t - \tau)] dt \quad \text{--- (9)}$$

Comparing the (9) and (1), it could be observed that the Stockwell transform can be expressed in terms of CWT. Considering $f = 1/a$, the correlation between ST and CWT [16] can be expressed as

$$ST(a, \tau) = M(a, \tau) W(a, \tau) \quad \text{--- (10)}$$

Where $M(a, \tau) = \frac{e^{-j2\pi\tau/a}}{\sqrt{a}}$. Hence, the S-transform is the CWT multiplied by a weight matrix $M(a, \tau)$, which consists of two terms $e^{-j2\pi\tau/a}$ and $1/\sqrt{a}$. The first term retains the phase of the original signal and the second term enriches the energy of the components of high frequency. With the help of S-transform the high frequency component can be represented in a better way in time-frequency spectrum [5]. Like SST, the second step in the direction of development of S-SST is the estimation of instantaneous frequency [5]. The instantaneous frequency of S-SST at any point (f, τ) with regard to τ is defined as

$$\tilde{f}(f, \tau) = f + \frac{1}{j2\pi ST(f, \tau)} \frac{\partial ST(f, \tau)}{\partial \tau} \quad \text{--- (11)}$$

The last step is reassignment or squeezing of the value of t-f spectrogram. The purpose of the reassignment is to assign a value to the instantaneous frequency. The S-SST of a signal $x(t)$ is represented as

$$SSST(\tilde{f}_l, \tau) = \frac{1}{\Delta \tilde{f}} \sum_{f_k: |\tilde{f}(f_k, \tau) - \tilde{f}_l| \leq \frac{\Delta \tilde{f}}{2}} |ST(f_k, \tau)| f_k \Delta f_k \quad \text{--- (12)}$$

where f_k is the discrete frequency of ST, $\Delta f_k = f_k - f_{k-1}$. The central frequency of the squeezed spectrum is represented as \tilde{f}_l and $\Delta \tilde{f}$ is the frequency interval of the squeezed spectrum, $\Delta \tilde{f} = \tilde{f}_l - \tilde{f}_{l-1}$.

III. RESULT AND DISCUSSION

The S-SST performances is demonstrated in comparison with ST and SST. For this purpose, one non-stationary synthetic signal and three real-time recorded earthquake signals are considered.

The parameters chosen in various T-F representations are listed in Table I.

TABLE I
PARAMETER USED IN T-F REPRESENTATION OF SYNTHETIC & REALTIME SIGNAL

| Signal | ST (window width factor = k) | SST (number of voices per octave = nv) | S-SST (number of voices per octave = nv) |
|--------------------|------------------------------|--|--|
| Synthetic signal | 3 | 64 | 64 |
| Seismic record 1,2 | 3 | 64 | 64 |

i. Non stationary Synthetic Signal

A synthetic signal is developed with three sinusoidal components to demonstrate the features of S-SST. Sampling frequency of the signal is 500 Hz and the signal noise ratio is 10 dB. The signal length is considered for 10 sec. The generated synthetic signal is represented as

$$x(t) = x_1(t) + x_2(t) + x_3(t) + x_4(t) + \eta(t)$$

$$x_1(t) = [1 + 0.25 \cos(2\pi t)][\cos(2\pi 30t + 0.25 \sin(2\pi t))]$$

$$0 \leq t \leq 3$$

$$x_2(t) = [2 + 0.35 \cos(2\pi t)][\cos(2\pi 15t + 0.25 \sin(2\pi 2t))]$$

$$3 \leq t \leq 6$$

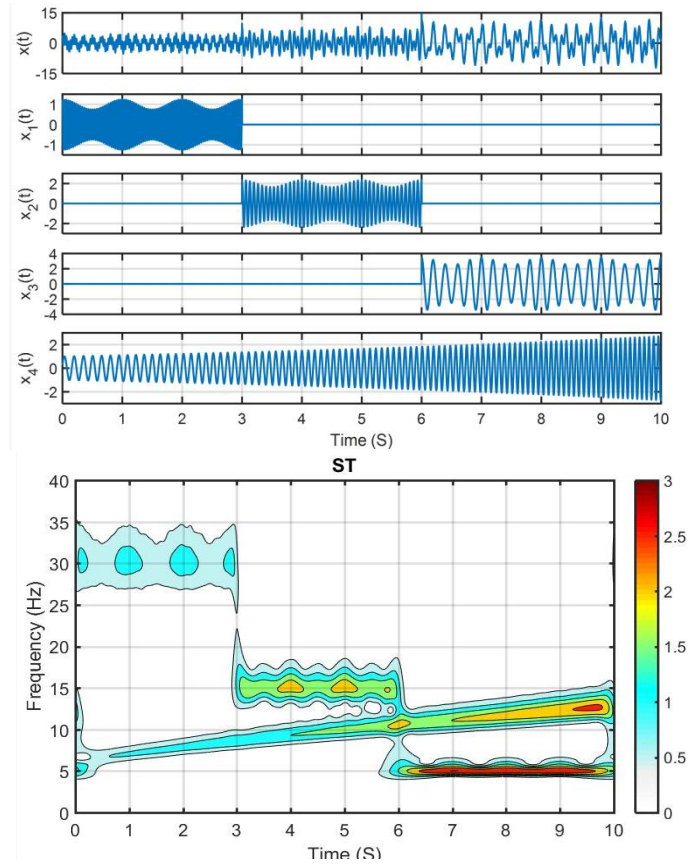
$$x_3(t) = [3 + 0.5 \cos(2\pi t)][\cos(2\pi 5t + 0.25 \sin(2\pi t))]$$

$$6 \leq t \leq 10$$

$$x_4(t) = e^{t/10}[\sin(2\pi(6t + 0.6t^{1.8}) + 0.3 \cos t)]$$

$$0 \leq t \leq 10 \quad \text{----- (13)}$$

where $\eta(t)$ is the Gaussian noise, the signal to noise ratio of 10 dB is added to the signal. Figure1 (a) shows the synthetic signal and its components considered for the analysis.



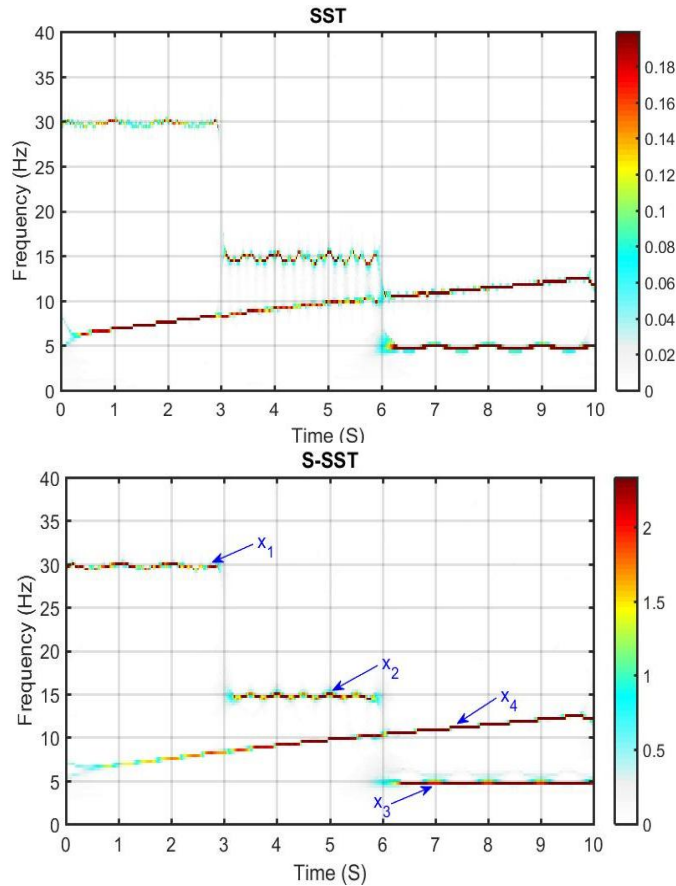


Figure 1. Time-Frequency representations of synthetic signal (a) $x(t)$ signal, and its components $x_1(t)$, $x_2(t)$, $x_3(t)$ and $x_4(t)$ (b) S-transform (c) SST (d) S-SST

The time-frequency representations of synthetic signal-1 based on ST, SST, SSST are displayed in Figure 1 (b), Figure 1 (c), and Figure 1 (d) respectively. Morlet wavelet is used to perform SST. The four components of $x(t)$ namely $x_1(t)$, $x_2(t)$, $x_3(t)$, and $x_4(t)$ are shown in Figure 1 (a). These four components are visible in all the three analysis of ST, SST, and S-SST T-F spectra. The $x_1(t)$ component is frequency modulated with low amplitude and high carrier frequency (30 Hz) with an interval of $0 \leq t \leq 3$, $x_2(t)$ is also an AM-FM component present for an interval of $3 \leq t \leq 6$, and the third component is an AM-FM component with low frequency component and high amplitude modulated signal, exists for an interval of $6 \leq t \leq 10$. The fourth component is chirp signal with increasing amplitude. The S-transform T-F spectra shows the good time localization, however, it exhibits frequency smearing characteristics which could be observed from the Figure 1 (b). It could distinguish between the low energy and high energy signals. The fourth component is also extracted from the synthetic signal with increasing amplitude except the frequency smearing. The time localization is clear at $t = 3$ sec, however at $t = 6$ sec shows an interference between the switching of second to third and fourth components. The CWT based synchrosqueezing with Morlet wavelet is computed for synthetic signal. The SST T-F spectra of synthetic signal is displayed in Figure 1 (c), which rectifies the problem of frequency smearing. The time localization is also good, however the interference at $t = 6$ is still present. The amplitude information of the four components are fairly distinguishable. The Stockwell-synchrosqueezing transform clearly distinguishes the four components with time localization and frequency localization, it could be observed from Figure 1 (d). The interference between the components is nullified at $t = 6$ sec. The amplitudes of each component, energy concentration are distinguishable between the components.

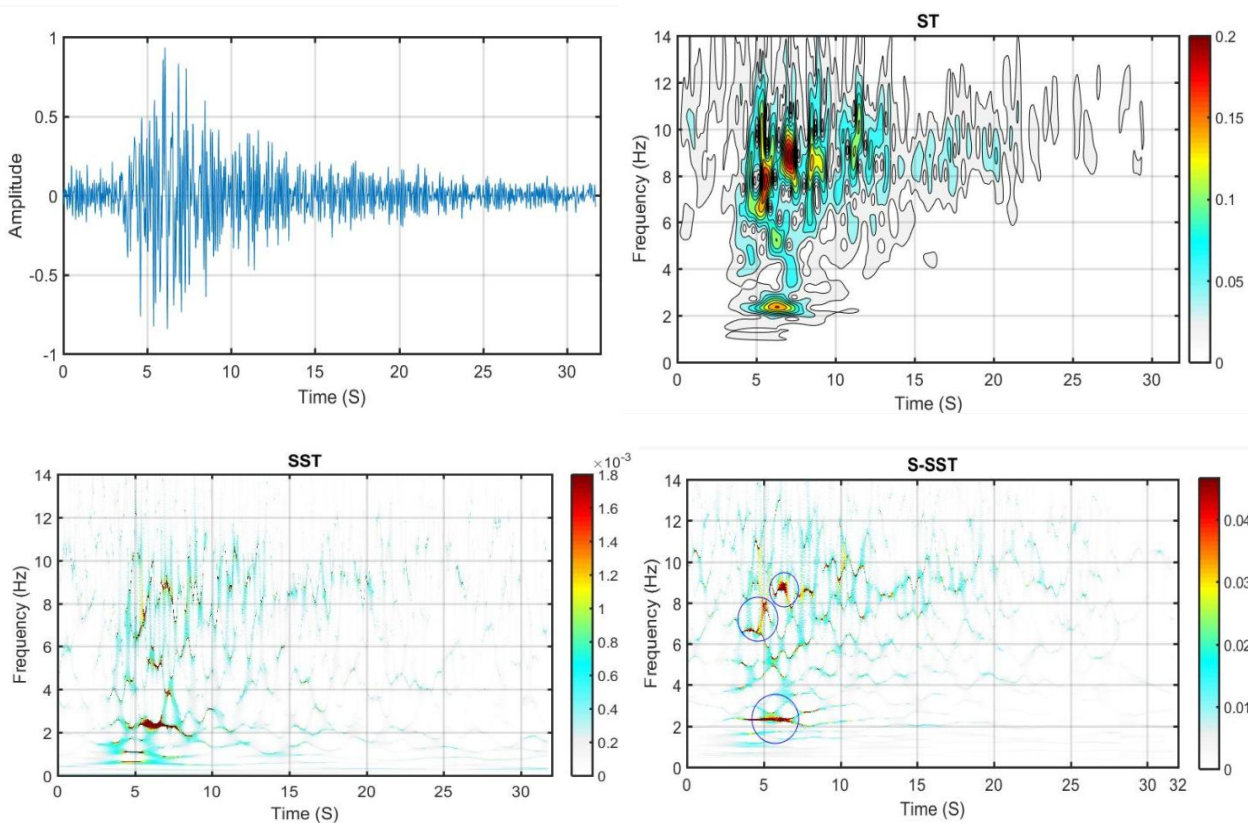


ii. Real-Time Earthquake Record 1

A strong motion array of 28 strong motion accelerographs were installed by Department of Earthquake Engineering, Indian Institute of Technology, Roorkee, India in 1991 in Garwhal Himalaya, under the research scheme of strong motion array funded by Department of Science and Technology, Govt of India. This network recorded many earthquake events including one catastrophic earthquake of Uttarkashi (1991). This first earthquake ground motion signal is of that drastic Uttarkashi earthquake occurred 20 October 1991 at 02:53 IST with a moment magnitude of 6.8, recorded at Badkot station (30.48N 78.13 E), one station of that SMA network. The signal was recorded by three component strong motion accelerograph made of Kinemetrics, USA. Instrument damping was 0.62 and the North-South component of seismogram is used for joint time-frequency representation. The signal was recorded having sampling frequency of 50 Hz and signal length is 31.74 sec. The acceleration time-history is shown in Fig. 2 (a) and Time-Freq. spectra of this seismic ground motion using ST, SST and S-SST is shown here in Figure 2 (b), Figure 2 (c), and Figure 2 (d).

The obtained result of S transform identified spots of concentration in energy with smearing between two frequency components and spectral overlap. The smearing effect is also appearing in the results of SST in both 2 to 3 Hz frequency component, and in 6.5 to 10 Hz frequency band.

The Figure 2 (e) shows the S-SST spectra with data cursor markings of region of interest. The S-SST spectra of the first record clearly shows the three concentrated energies of 2.3 - 2.26 Hz for 4.8 - 6.8 sec, 6.6 - 7.8 Hz for 4.55 - 5.05 sec, and 8.8 - 7.9 Hz for 6.25 - 6.79 sec.



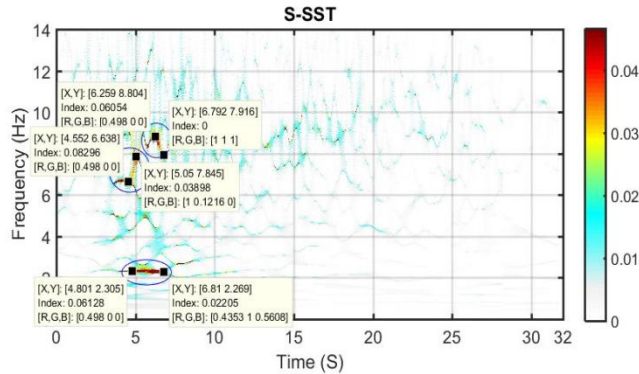
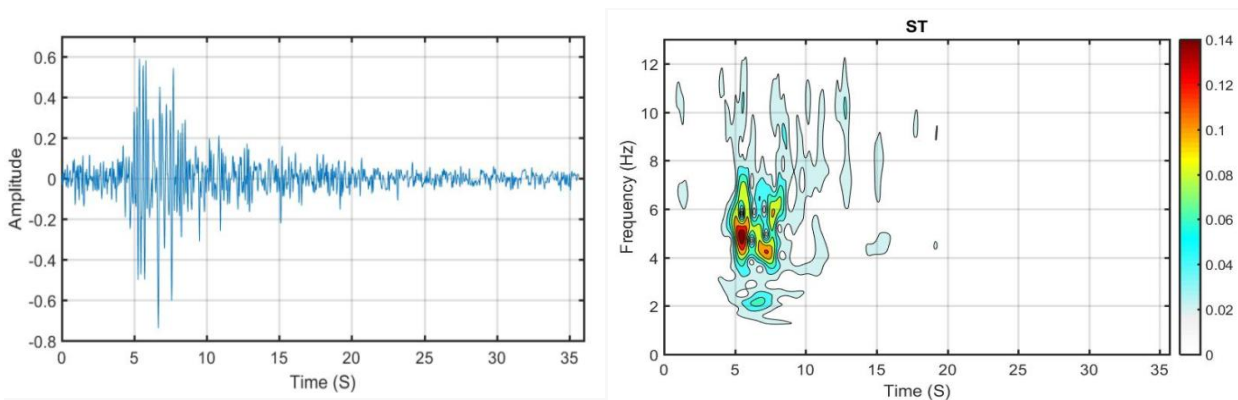


Figure 2. Time-Frequency representations of Badkot station time-history (a) Accelerogram (b) S-transform (c) SST (d) S-SST (e) S-SST with data cursor

iii. Real-Time Earthquake Record 2

The second ground motion record used in our analysis is of same Uttarkashi Earthquake recorded at another station named Purola, Uttarakhand, India 30.52 N 78.50 E. The signal was recorded by three component strong motion accelerograph made of Kinematics, USA. Instrument damping was 0.58 and the North-South component of seismogram is used for obtaining the JTF representation. The signal was recorded with a sampling frequency of 50 Hz and the record time was 35.70 sec. The acceleration timehistory is shown in Figure 3 (a) and the t-f spectra of seismic signal using ST, SST as well as S-SST is shown in Figure 3 (b), Figure 3 (c), and Figure 3 (d) respectively. Because of reduced spectral overlapping comparatively ST and reduced smearing effect comparatively SST, the S-SST spectra of the second record shows the two predominant concentrated energies of 5.42 - 4.32 Hz for 4.52 - 5.68 sec, 4.32 - 4.25 Hz for 6.6 - 7.7 sec



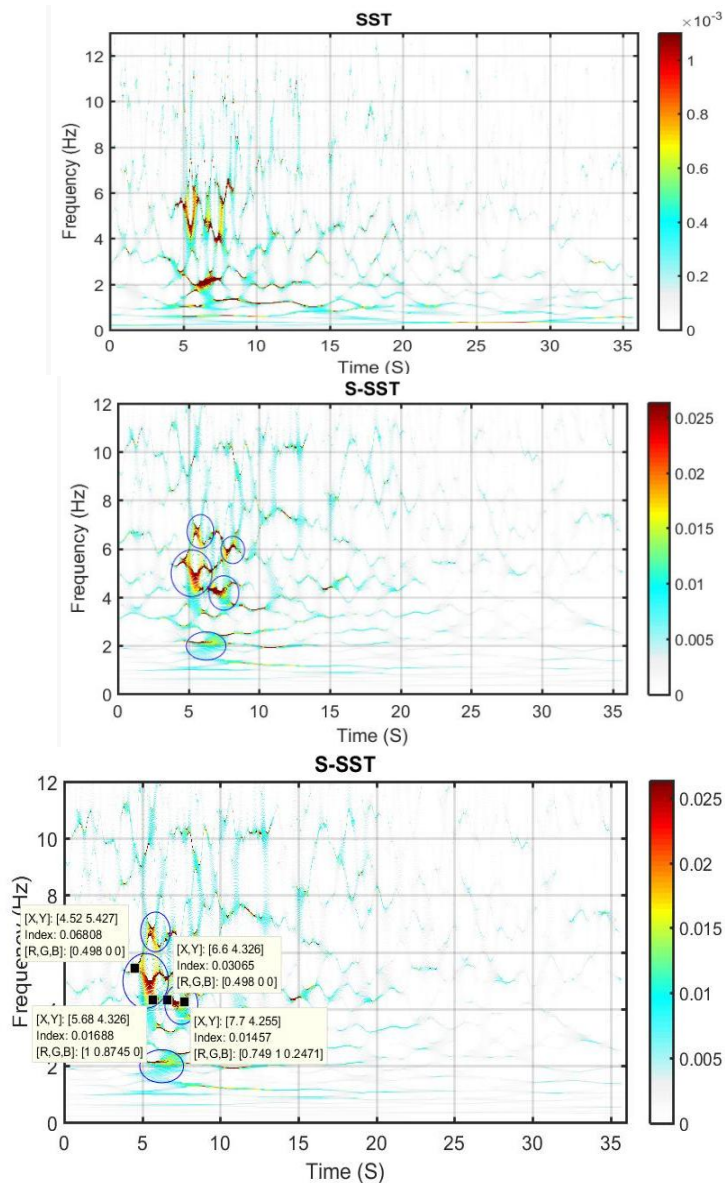


Figure 3. Time-Frequency representations of Purola station time-history (a) Accelerogram (b) S-transform (c) SST (d) S-SST (e) S-SST with data cursor

IV. CONCLUSION

The Stockwell transform based synchrosqueezing approach has been introduced for seismic signals and validated for real-time ground motion signals. The qualities of S-transform and synchrosqueezing are combined by exploiting the relation between S-transform and CWT. The relation between them reveals that a weight matrix could change the CWT based synchrosqueezing to ST based synchrosqueezing. The clear energy concentrations present in the T-F spectra of S-SST reveal the meaningful interpretation of the seismic signal. Moreover, the S-SST offers good frequency localization and time localization. It could be concluded that the S-SST is a potential tool for analyzing the seismic signals.

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