Journal of the Earth and Space Physics, Vol. 44, No. 4, Winter 2019, P. 41-51

DOI: 10.22059/jesphys.2018.249021.1006959

Application of Single-Frequency Time-Space Filtering Technique for Seismic Ground Roll and Random Noise Attenuation

Radad, M.*

Assistant Professor, Department of Petroleum and Geophysics, Faculty of Mining, Petroleum and Geophysics Engineering, Shahrood University of Technology, Shahrood, Iran

(Received: 31 Dec 2017, Accepted: 15 May 2018)

Abstract

Time-frequency filtering is an acceptable technique for attenuating noise in 2-D (time-space) and 3-D (time-space-space) reflection seismic data. The common approach for this purpose is transforming each seismic signal from 1-D time domain to a 2-D time-frequency domain and then denoising the signal by a designed filter and finally transforming back the filtered signal to original time domain. The technique is efficient for ground roll and also random noise attenuation. However, if we deal with a large data set and a great number of contaminated signals with ground roll noise, a much move consuming time will be required. In this paper, time-frequency filtering is formulated and carried out by a different approach. The data is transformed from original time-space domain into several single-frequency time-space domains, and the filters to reduce noise is designed in the new domains. The transform is easily and completely invertible. The employed time frequency analysis method is a high-resolution version of S-transform. Application to synthetic and real shot gathers confirms the good performance and efficiency of the method for attenuating ground roll noise and random noise.

Keywords: Time-frequency analysis, Single-frequency section, Filtering, Seismic noise.

1. Introduction

Time-frequency (tf) analysis is a mathematical technique that allows transforming a time series from 1D time domain to 2D time-frequency domain. Through this approach numerous applications have been developed in seismic data processing and interpretation. There are several t-f analysis methods including windowed Fourier transforms such as Gabor transform (Gabor, 1946) and S-transform (Stockwell et al., 1996), wavelet based transforms such as continuous wavelet transform (Mallat, 1999) and Cohen class distributions such as Wigner-Ville distribution (Wang, 2010; Wu and Liu, 2009). Besides, some tf methods are based on an inversion problem (Liu and Fomel, 2013; Liu et al., 2011). In the windowed Fourier based t-f transform scheme, a t-f map of a signal can be provided via two approaches of windowing the signal or windowing its Fourier representation through a unified formulation (Radad et al., 2015). By employing the second approach, Radad et al. (2016) generated single-frequency time-space (t-x) sections in a fast way for some seismic interpretational applications. They showed that for generating an interested single-frequency t-x section, it is sufficient to window the Fourier transform of signal around the intended frequency and leave alone other components. In this paper, the approach is employed as a filtering technique to attenuate seismic ground roll noise and also random noise, as the most dominant types of noise existing on reflection seismic data.

The most common approach to attenuate noise is transforming data from original domain to a new domain where it would be possible to separate the unwanted noise from wanted signal. However, in new domain, there must be a discrimination and separation measure between noise and data. Concerning about ground roll noise, the properties of the noise that could be employed as discrimination measures are high amplitude (Jiao et al., 2015; Porsani et al., 2010; Montagne and Vasconcelos, 2006; Liu, 1999), low frequency (Yilmaz, 2001), low velocity (Yarham et al., 2006; Yilmaz, 2001; Tartham et al., 1983; Wiggins, 1966), and frequency dispersion (Bekara and van der Baan; 2009; Askari and Siahkoohi, 2008; Deighan and Watts, 1997). The dispersive nature of the ground roll means that the

*Corresponding author: mradad@shahroodut.ac.ir

different wavelengths (or frequency modes) of ground roll are impressed by different velocity distributions and hence they propagate with various velocities (Al-Husseini et al., 1981). It means that there is a significant overlap of noise and signal, and attenuation of the noise require a powerful tool to separate it from favorite data. Askari and Siahkoohi (2008) shows that t-f based technique is able to separate noise from data in a good level, particularly in case of a high dispersive distribution of ground roll; however, the filtering process is time-consuming and needs high precision of user. In this paper, a new aspect of Fourier based t-f analysis is considered that tackles this limitation of t-f filtering. The approach of this paper for attenuating ground roll is transforming seismic data from original t-x domain, which includes the entire modes of ground roll, to a series of t-x sections which would contain single-frequency components (individual modes). Through this way, a nice attempt could be done to retain the data while attenuating noise as much as possible. This mission is feasible using t-f analysis of data to generate single-frequency t-x sections. It can be assumed that each single-frequency t-x section comprises a specific mode of ground roll wave.

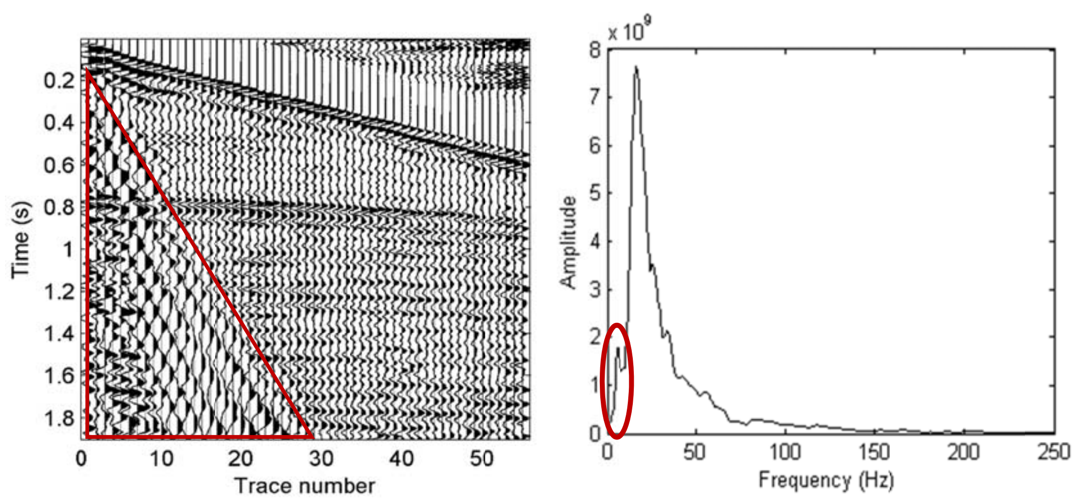
Another purpose of this paper is suppressing random noise. The common technique of random noise reduction is low pass filtering. This process is easy; however, it is probable that some level of data is also attenuated. In the approach of this paper, it is feasible to attenuate random noise in addition to ground roll noise attenuation. The technique is that with monitoring single-frequency t-x sections in higher frequencies, the sections with no effect on favorite data (reflection events) can be assumed as random noise effect and can be excluded from reconstruction.

2. Theoretical Background

The ground roll noise on the seismic shot gather is appeared as a rectangle t-x distribution as shown in Figure 1(a). According to dispersive nature of ground roll noise on the location that seismic recording is done and also based on the parameters of seismic data acquisition, the t-x distribution of ground roll can be different. Another point about ground roll noise is that its frequency band is usually below 15 Hz, which this point is seen on Figure 1(b).

2-1. x-t-f filtering

The common approach of ground roll noise filtering by t-f analysis is seeking for ground roll distribution on the t-f map of each seismic signal (each x coordinate) and trying to filter it (as shown in Figure 1) (Askari and Siahkoohi, 2008). The inverse t-f transform brings back the filtered signal to time domain. The procedure is performed for all contaminated traces. This strategy can be called x-t-f filtering.



(a) (b)

Figure 1. a) A real seismic shot gather, including 57 traces or signals (at different offsets or xs), and contaminated with a dominant ground roll noise whose t-x distribution is remarked by a colored rectangle on the image. b) Average amplitude spectrum of the gather in which the ground roll effect is remarked by colored ellipse.

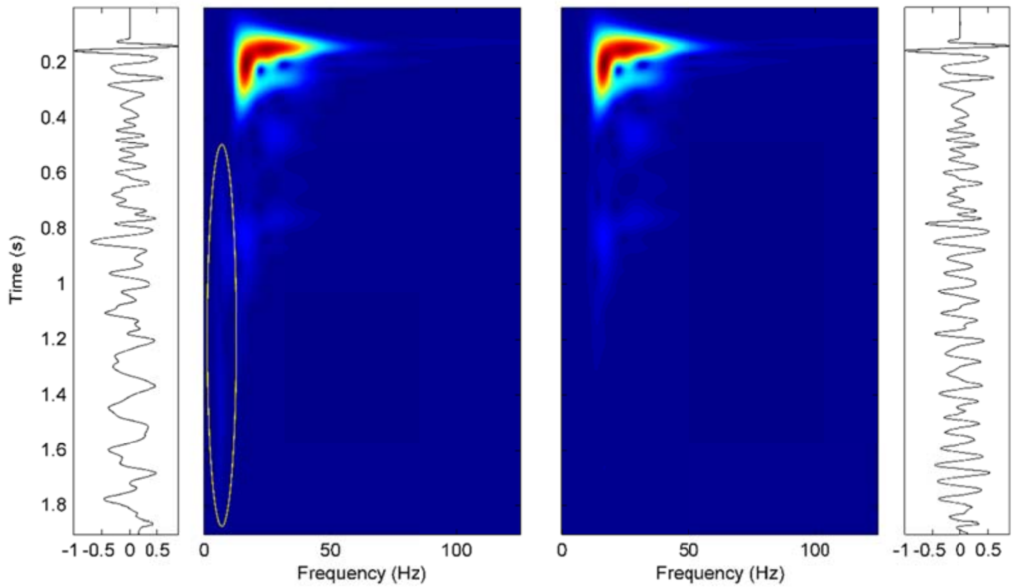


Figure 2. Ground roll attenuation in a sample seismic signal (a) by x-t-f filtering (Askari and Siahkoohi, 2008). (b) tf map of (a) which in the ground roll distribution is remarked by yellow ellipse; (c) is filtered tf map; and (d) filtered seismic signal constructing by inverse t-f transform of (c).

In spite of considerable performance for separating noise and favorite data, there are some practical problems with the x-t-f filtering technique. This technique needs high consuming time for denoising, besides the tracking ground roll distribution on the tf map is almost cumbersome and needs high level of precision. These problems could be more severe when we would deal with a large number of contaminated seismic signals with ground roll noise and when there would be a severe dispersion.

2-2. f-t-x filtering

Here, as a new approach of t-f filtering, a solution to the problems of x-t-f filtering is presented. The technique is considering x-t-f domain from another perspective of f-t-x filtering. It means that, instead of making t-f plane for each seismic signal at x coordinate, it is better to make t-x plane for each frequency component (single-frequency t-x sections). There are some merits with this technique. Since a rather narrow frequency band (generally up to 15 Hz) corresponds to ground roll noise, it is sufficient to make t-x planes for this number of frequency components. This is regardless of the number of contaminated traces; and therefore, the consuming time for filtering could be significantly reduced. Another point is about tracking ground roll distribution by user, which seems to be obviously easier to do in t-x domain than t-f domain. However, the remarkable advantage of f-t-x filtering is about monitoring t-x domain of each individual mode which allows the user to tackle the dispersion issue with more precision.

Another efficient aspect of this technique is tackling the random noise. Inspired by high cut filtering to reduce random noise, with monitoring single-frequency t-x sections in f-t-x filtering procedure for high frequencies, the sections not presenting any effect of favorite data (reflection events) can be assumed as random noise effect and can be excluded from reconstruction.

The technique to generate single-frequency t-x sections is the one proposed by Radad et al. (2016). This procedure can be briefly explained as: i) transforming the data from t-x domain to f-x domain by Fourier transforming the whole seismic signals; ii) windowing the spectra around the intended frequency to make local f-x domain; iii) inverse Fourier transforming the result along frequency to get single-frequency t-x section. In the following, a description of formulation of f-t-x filtering is presented.

2-2-1. Formulation

Having a given seismic t-x section, $D\,(\mathrm{t,x})$, the f-x representation can be obtained by Fourier transforming along the time axis:

$$\hat{D}(f,x)=F\{D(t,x)\}, \tag{1}$$

where hat sign, $, represents the Fourier domain and F represents the Fourier transform operator. Then a window matrix can be defined to provide a localized f-x representation around an intended frequency f_i :

$$\hat{D}^{(f_i)}(f,x)=\hat{D}(f-f_i,x)\hat{W}^{(f_i)}\left(f,x\right), \tag{2}$$

where $\hat{W}^{(f_i)}\left(f,x\right)=\hat{w}^{(f_i)}\left(f\right),\ \forall x$. $\hat{w}^{(f_i)}\left(f\right)$ can be defined as a window in the frequency domain with any arbitrary function. Radad et al. (2016, 2015) showed that a high-resolution t-f map can be reached with employing an optimization problem and using some energy concentration measures to find optimum windows. Here, by this approach, optimum widths (as the standard deviation proportional to inverse of frequency) for a Gaussian function of $\hat{w}^{(f_i)}\left(f\right)=e^{-\frac{2\pi^2 f^2}{f_i^2}}$ using energy concentration measure of Gini index (Radad et al., 2015) has been found and employed. For each frequency component f_i , an optimum window can be found and employed in Equation (2). Then the single-frequency t-x section is obtained by inverse Fourier transforming along frequency as:

$$D^{(f_i)}(t,x)=F^{-1}\{\hat{D}^{(f_i)}(f,x)\}, \tag{3}$$

where F^{-1} represents the inverse Fourier transform operator. The inverse transform to original t-x domain includes: i) augmenting the single-frequency t-x sections by frequency dimension to make a f-t-x array; ii) projecting the obtained array on the frequency axis to reach f-x section; and finally iii) inverse Fourier transforming along frequency dimension to obtain t-x section:

$$\tilde{D}(t,x)= F^{-1}\left\{D^{(f_1)}(t,x)\,|\,D^{(f_2)}(t,x)\,|\,...\,|\,D^{(f_{\max})}(t,x)\right\}, \tag{4}$$

where tilde sign is chosen as a notation for inverse or synthesis transform; $\mathrm{A}\,|\,\mathrm{B}$ is as augmentation of arrays A and B. If the data size is large, in the inverse procedure, the sequence of augmentation and projection steps (i and ii) can be exchanged. It means that we can perform, at first, projecting single-frequency t-x sections on x dimension and then augmenting the projections along frequency to reach f-x section. It is worthful to be mentioned that the employed windows $\hat{w}\left(f\right)$, used in Equation (2) have to satisfy the partition of unity criteria, $\int_{-\infty}^{\infty}\hat{w}(f)df=1$, so that inverse transform would be completely invertible.

If no manipulation is applied on none of the single-frequency t-x sections $D^{(f_k)}(t,x),\ k=1,...,N$, and all of them are included in the synthesis, the maximum frequency, $f_{\max}$ will be Nyquist frequency and so $\widetilde{D}(t,x)=D(t,x)$. In this study, some manipulations (muting operations) are to be applied on some single-frequency t-x sections (to attenuate ground roll), and besides the entire individual $D^{(f_k)}(t,x)$ sections are not to be included in synthesis (to suppress random noise). If $G^{(f_k)}(t,x)$ is a typical t-x muting operator suggested to be applied on some single-frequency t-x sections $D^{(f_k)}(t,x)$ (including ground roll), then filtered single-frequency t-x sections will be as:

$$Q^{(f_i)}(t,x)=D^{(f_i)}(t,x)G^{(f_i)}(t,x). \tag{5}$$

For the single-frequency t-x sections that need to be leaved alone (including just favorite reflection data), $G(t,x)=1$, and for those which are to be excluded from synthesis (including just random noise and no reflection data), $G(t,x)=0$. Therefore, synthesis formulation to generate filtered t-x domain, $\tilde{Q}(t,x)$, will be defined as:

$$\tilde{Q}(t,x) = F^{-1}\left\{Q^{(f_1)}(t,x) \,|\, Q^{(f_2)}(t,x) \,|\, ... \,|\, Q^{(f_{\max})}(t,x)\right\}. \tag{6}$$

Figure 3 shows a flowchart explaining the f-t-x filtering algorithm.

3. Implementation

3-1. Synthetic data

Figure 4(a) shows a synthetic seismic shot gather that includes seven reflection events (favorite data) with different zero-offset times and velocities (curves). A minimum phase wavelet with dominant frequency of 25 Hz is employed to synthesize data and time sampling interval is two milliseconds. Some trains of ground roll waves with evident frequency dispersion and gaussian random noise with signal to noise ratio of 2 were added to the shot gather, the result of which is shown in Figure 4(b). The average amplitude spectra of the shot gathers shown in Figures 4(a) and 4(b) are respectively presented in black and red in Figure 5. As seen, there are evident frequency band overlaps between reflection events and ground roll waves in low frequencies and between reflection events and gaussian random noise in high frequencies.

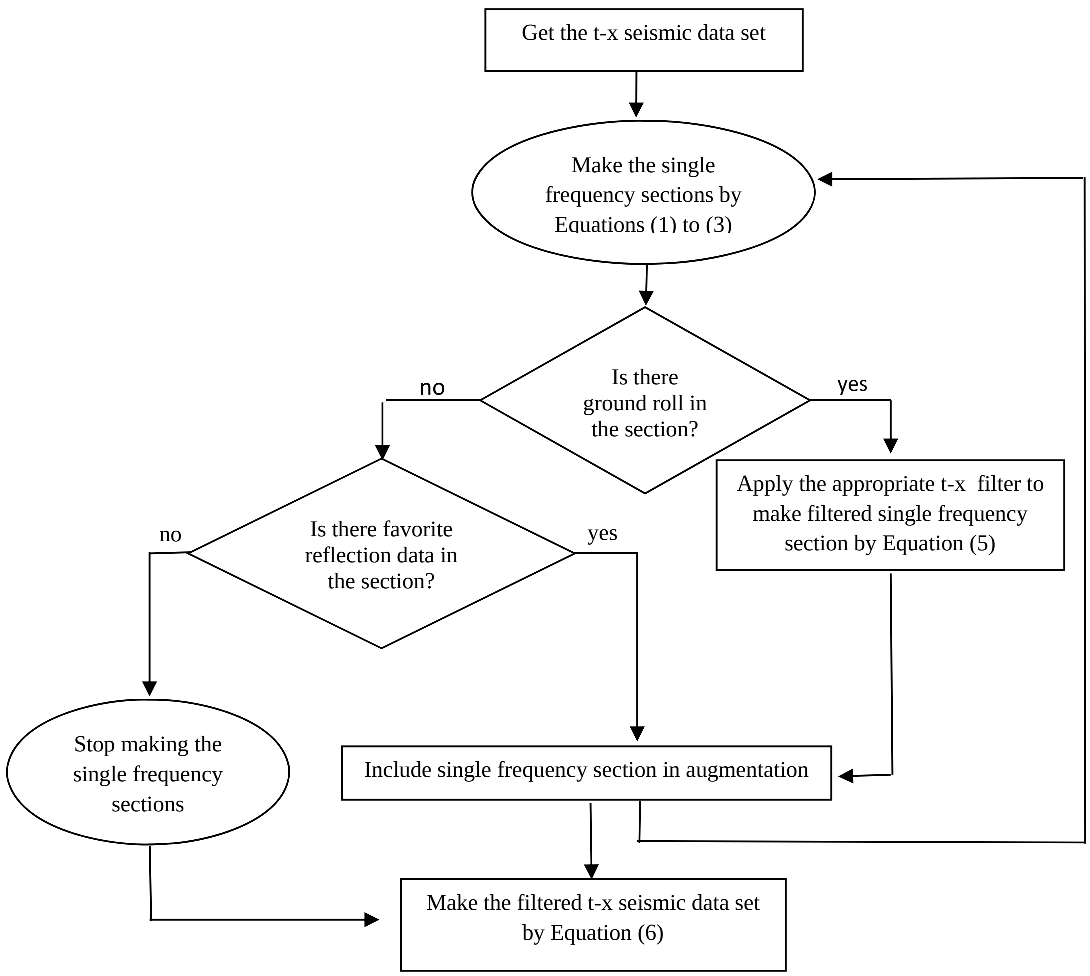
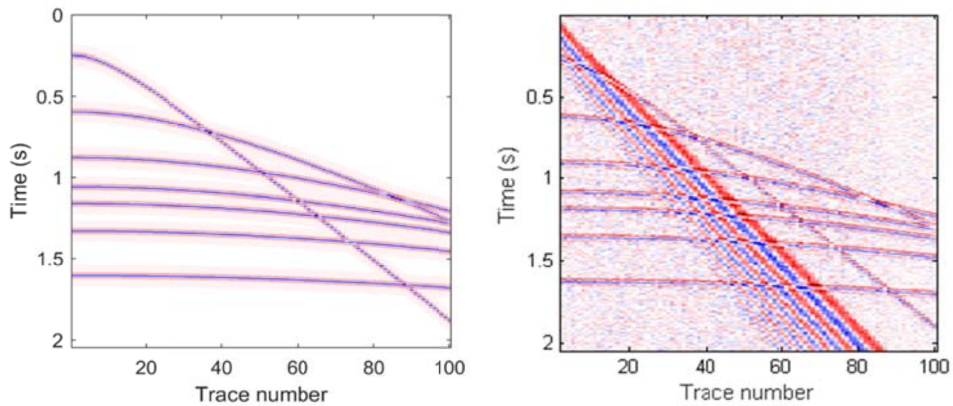


Figure 3. The flowchart of f-t-x filtering algorithm.



(a) (b)

Figure 4. A synthetic seismic shot gather without any noise (a) and contaminated with ground roll and random noise (b).

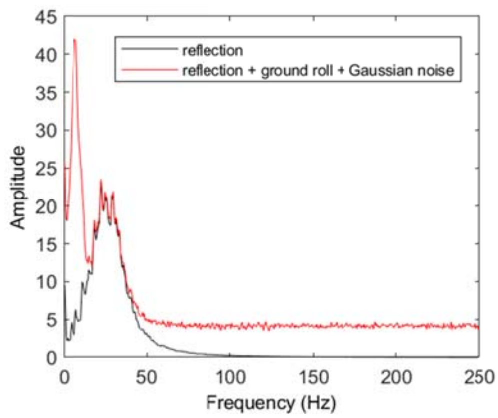


Figure 5. Average amplitude spectra related to synthetic shot gathers shown in Figures 4a (black) and 4c (red).

The shot gather shown in Figure 4(b) was analyzed to obtain single-frequency t-x sections. As some sample sections, Figures 6(a) to (f) show six single-frequency t-x sections of 6 Hz, 9 Hz, 12 Hz, 15 Hz, 28 Hz and 80 Hz. Monitoring these sections reveals dispersion pattern of ground roll. As seen, the velocity of ground roll (the inverse of dip in t-x plain) differs on each single-frequency t-x section, so that the velocity of ground roll decreases with frequency. Therefore, each section includes a few modes of ground roll, as expected. Afterwards, as seen, the 28 Hz section includes no ground roll noise and the 80 Hz section does not have any value of reflection events. In the f-t-x filtering process, these tasks can be carried out: i) filtering out ground roll t-x distribution from each single-frequency t-x section (for example, the area shown in Figure 6d); ii) leaving alone the single-frequency t-x section including no ground roll; iii) excluding single-frequency t-x sections with no reflection events from synthesis process. Through this procedure, one can attenuate ground roll noise and suppress a significant part of random noise and therefore increase signal to noise ratio.

A noticeable point of f-t-x analysis of the seismic data is that it can also help in designing appropriate filed acquisition parameters to record ground roll waves as less as possible. This is possible by having the ground roll wavelengths that can be determined through the velocity and the frequency of different modes of ground roll distributed on different single-frequency t-x sections. Some filed acquisition approaches to suppress ground roll are discussed in Knapp and Steeples (1986). However, this issue is not studied in this paper.

There are some technical points in f-t-x filtering about consuming time. For ground roll attenuation, it is sufficient to generate single-frequency t-x sections up to the frequency where in the ground roll noise would be evident (for example, 15 Hz) and perform filtering these sections. On the other hand, for random noise attenuation, one can make a good estimation about the highest frequency that one guesses the reflection data that would be present (for example 75 Hz). It is sufficient to generate single-frequency t-x sections from this estimated frequency (and by necessary checking out the existence of reflection data on this single-frequency t-x section) up to the frequency where in the reflection data would be disappeared. The experience with the data used for this paper shows that an octave after the dominant frequency of the average spectrum of the data would be an appropriate estimation for the high limit of frequency band of reflection data. On the other words, there is no necessity to generate the entire single-frequency t-x sections for monitoring and inverse transform or synthesis can be carried independent on generating the whole single-frequency t-x sections.

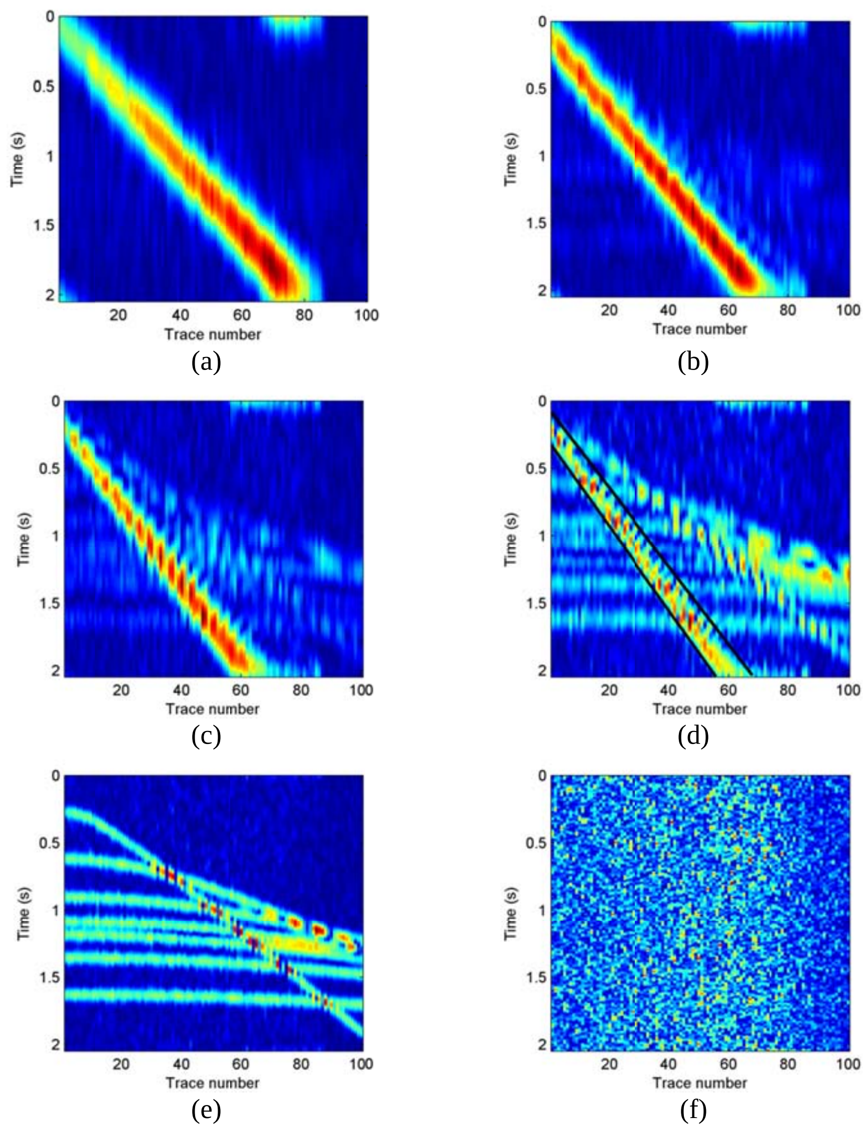


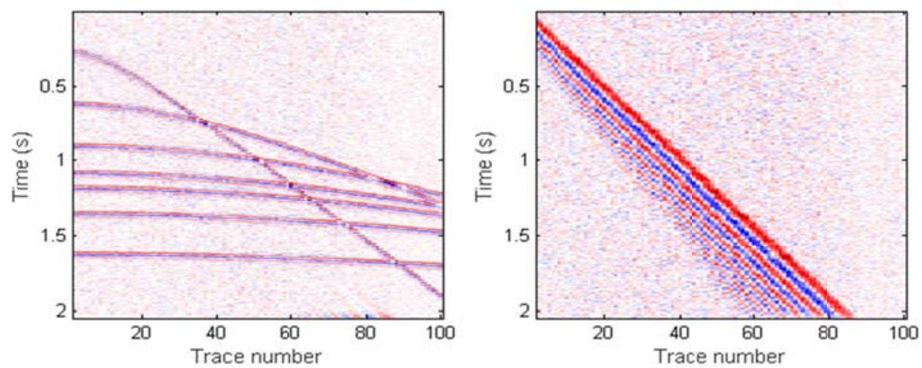
Figure 6. (a) to (f) show single-frequency t-x sections of frequencies 6 Hz, 9 Hz, 12 Hz, 15 Hz, 28 Hz and 80 Hz, respectively, analyzed from shot gather shown in Figure 4(c). As an example, the t-x distribution of ground roll is remarked on 15 Hz section (d) which needs to be filtered.

Figure 7 shows the result of filtering process applied on shot gather shown in Figure 4(b). The filtered section and the difference section (eliminated noise) are shown in Figures 7(a) and 7(b), respectively. As seen, the ground roll noise has been attenuated significantly and besides the data has been cleaned up from random noise acceptably. Figure 8 has been provided to present the performance of f-t-x filtering where in the average amplitude spectra of the synthetic shot gather before filtering (black curve in the figure) and after filtering (red curve in the figure) are compared. As seen in the figure, the amplitude of low frequency components (the ground roll region) has been reduced to level of spectrum of noise free data and the amplitude of high frequency components (the random noise region) has been reduced in a steep slope.

3-2. Real data

As the real experiment, the technique were applied on two real data sets. Figure 9(a) shows a real shot gather contaminated by ground roll noise. The time sampling interval of data is four milliseconds. The filtered shot gather by f-t-x filtering technique and the difference section are shown in Figures 8(b) and 8(c). As seen, the noise has been significantly attenuated, as it is observed in difference section. Amplitude spectra of data before filtering (black curve) and after filtering (red curve) have been shown in Figure 10.

Another real seismic shot gather contaminated with a highly dispersive ground roll and the amplitude is shown in Figure 11(a). The proposed f-t-x filtering is applied on the data to attenuate ground roll and random noise and the result are shown in Figure 11(b). As seen in the result, the f-t-x filtering has been able to attenuate ground roll in an acceptable level and some reflection hyperbola which had been masked by ground roll in the original data (Figure 11(a)) have been recovered. The difference section (Figure 11 (c)) shows the attenuated ground roll and random noise by the technique.



(a) (b)

Figure 7. (a) The result of f-t-x filtering applied on shot gather, shown in Figure 4(b), to attenuate ground roll and suppress random noise. (b) The difference section or the eliminated noise.

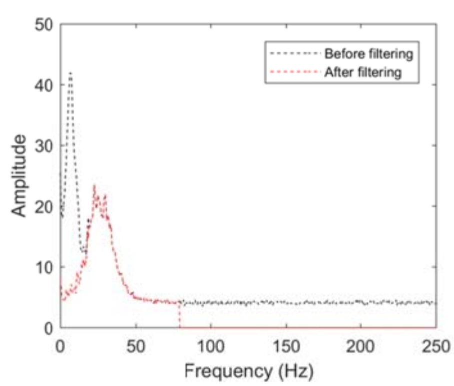
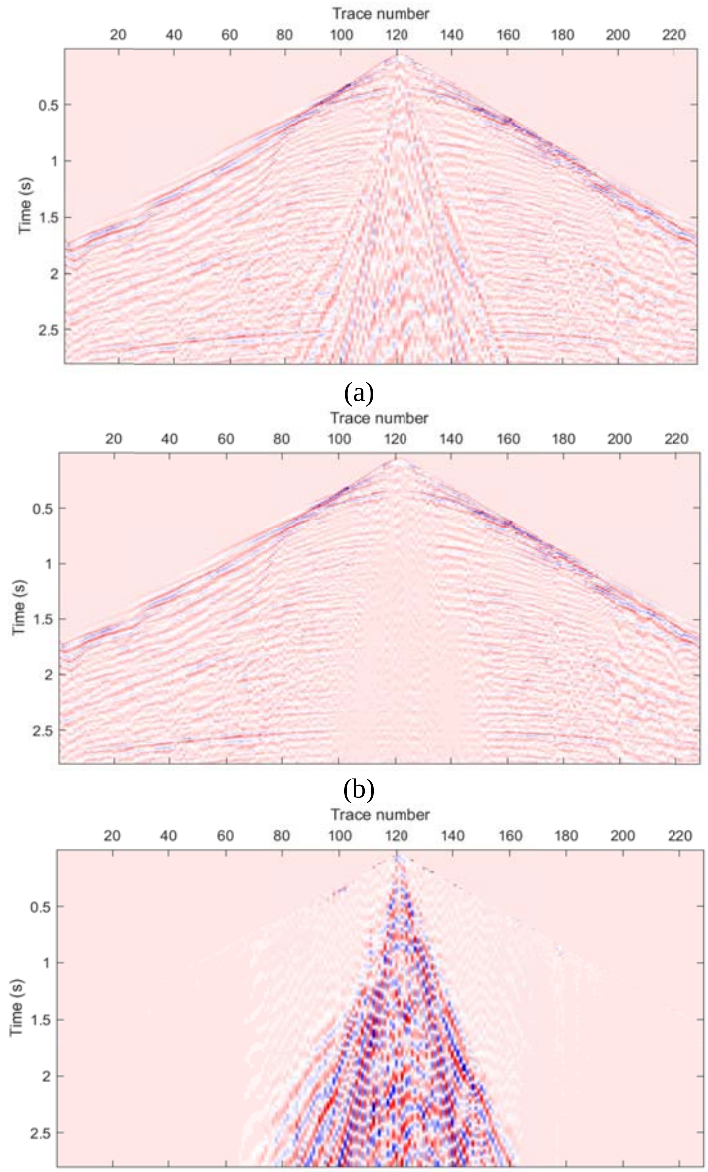


Figure 8. Average amplitude spectra related to synthetic shot gathers shown in Figures 4b (before filtering) and 7a (after filtering).



(a)

(b)

(c)

Figure 9. A real shot gather, before (a) and after (b) f-t-x filtering. The difference section of (a) and (b), as the removed noise is shown in (c).

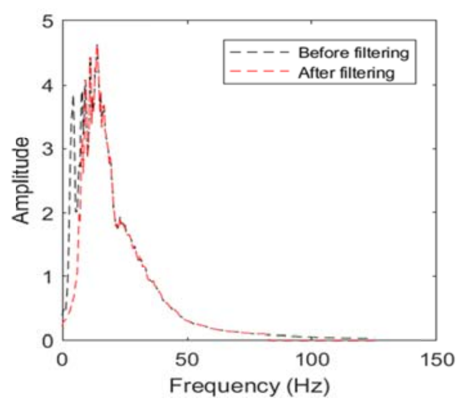


Figure 10. Average amplitude spectra related to synthetic shot gathers shown in Figures 9a (before filtering) and 9b (after filtering).

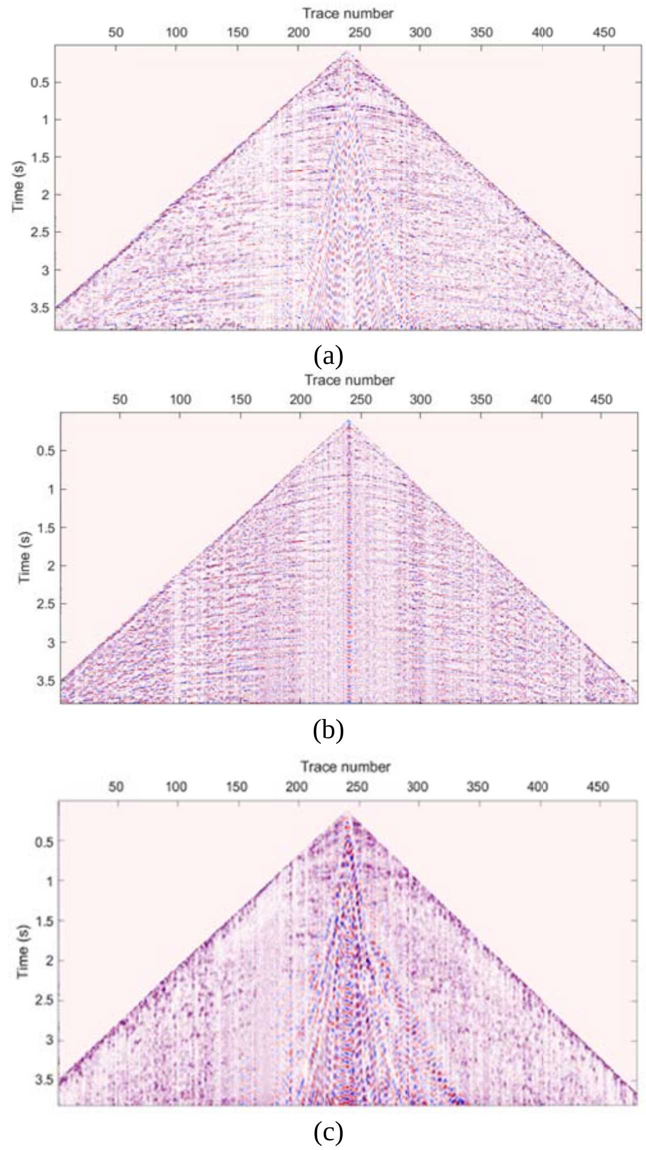


Figure 11. A real shot gather before (a) and after ground roll noise attenuation by proposed f-t-x filtering (b). The difference section of (a) and (b), as the removed noise (ground roll and random) is shown in (c). For better visualization of data, an AGC process to gain weak amplitudes has been applied to the figures.

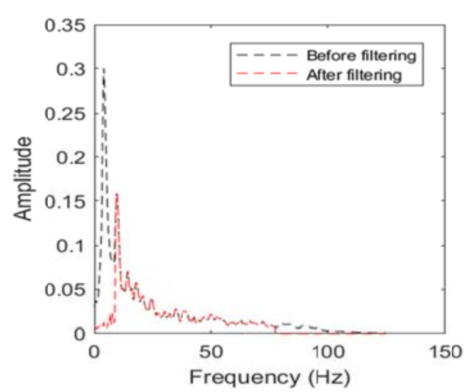


Figure 12. Average amplitude spectra related to synthetic shot gathers shown in Figures 11a (before filtering) and 11b (after filtering).

4. Conclutions

In this paper, a new aspect of t-f analysis of reflection seismic data was studied. It was shown that we can transform the seismic data from original t-x domain into analyzed single-frequency t-x domains to design appropriate f-t-x filters for separating different events based on their various t-x distributions on each single-frequency t-x section. It was also shown that a reconstruction formulation can be defined to turn back to the original t-x domain. Saving processing time and easier filtering are distinct properties of the approach compared to common x-t-f filtering that makes t-f filtering more efficient. In this paper, by this approach, ground roll noise and random noise were attenuated from synthetic and real seismic data in an acceptable level with tackling dispersion nature of ground roll waves.

References

Al-Husseini, M. I., Glover, J. B. and Barley, B. J., 1981, Dispersion patterns of the ground roll in eastern Saudi Arabia, Geophys., 46, 121-137.

Askari, R. and Siahkoohi, H. R., 2008, Ground roll attenuation using the S and x-f-k transforms. Geophys. Prospect, 56, 105-114.

Bekara, M. and van der Baan, M., 2009, Random and coherent noise attenuation by empirical mode decomposition. Geophys, 74, V89-V98.

Deighan, A. J. and Watts, D. R., 1997, Ground-roll suppression using the wavelet transform. Geophys, 62, 1896-1903.

Gabor, D., 1946, Theory of communication. J. Inst. Electr. Eng., 93, 429–457.

Jiao, S., Chen, Y., Bai, M., Yang, W., Wang, E. and Gan, S., 2015, Ground roll attenuation using non-stationary matching filtering. J. Geophys. Eng., 12, 922.

Knapp, R. W. and Steeples, D. W., 1986, High-resolution common-depth-point reflection profiling: field acquisition parameter design. Geophys., 51, 283-294.

Liu, G., Fomel, S. and Chen, X., 2011, Time-frequency analysis of seismic data using local attributes. Geophysics, 76, P23-P34.

Liu, X., 1999, Ground roll suppression using the Karhunen-Loeve transform. Geophys., 64, 564-566.

Liu, Y. and Fomel, S., 2013, Seismic data analysis using local time-frequency decomposition. Geophysical Prospecting, 61, 516-525.

Mallat, S., 1999, A Wavelet Tour of Signal Processing. Second ed., Academic Press, San Diego, California.

Montagne, R. and Vasconcelos, G. L., 2006, Optimized suppression of coherent noise from seismic data using the karhunen-Loeve transform. Phys. Rev. E., 74, 1-9.

Porsani, M. J., Silva, M. G., Melo, P. E. M. and Ursin, B., 2010, SVD filtering applied to ground-roll attenuation. J. Geophys. Eng., 7, 284.

Radad, M., Gholami, A. and Siahkoohi, H. R., 2015, S-transform with maximum energy concentration: application to non-stationary seismic deconvolution. J. Appl. Geophys., 118, 155-166.

Radad, M., Gholami, A. and Siahkoohi, H. R., 2016, A fast method for generating high-resolution single-frequency seismic attributes. J. Seism. Explor., 25, 11-25.

Stockwell, R. G., Mansinha, L. and Lowe, R., 1996, Localization of the complex spectrum: The S-transform. IEEE Trans. Sig. Process., 44, 998-1001.

Tartham, R. H., Keeney, J. W. and Noponen, I., 1983, Application of the tau-p transform (slant-stack) in processing seismic reflection data. Explor. Geophys., 14, 163-172.

Wang, Y., 2010, Multichannel matching pursuit for seismic trace decomposition. Geophys., 75, V61-V66.

Wiggins, R. A., 1966, W-K filter design. Geophys. Prospect., 14, 427-440.

Wu, X., and Liu, T., 2009, Spectral decomposition of seismic data with reassigned smoothed pseudo Wigner-Ville distribution. J. Appl. Geophys., 68, 386-393.

Yarham, C., Boeniger, U. and Herrmann, F. J., 2006, Curvelet-based ground roll removal. 76th Annual International Meeting, SEG, 2777-2780.

Yilmaz, O., 2001, Seismic data analysis. SEG, Tulsa, OK.