Journal of Applied Geophysics 128 (2016) 8–17

Contents lists available at ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

Ground-roll noise extraction and suppression using high-resolution linear Radon transform

Yue Hu [a,b], Limin Wang [a,b,*], Feng Cheng [a,b], Yinhe Luo [a], Chao Shen [a,b], Binbin Mi [a,b]

[a] Hubei Subsurface Multi-scale Imaging Key Laboratory, China University of Geosciences, 388 Rumo Rd., Wuhan, Hubei 430074, China
[b] Subsurface Imaging and Sensing Laboratory, Institute of Geophysics and Geomatics, China University of Geosciences, 388 Rumo Rd., Wuhan, Hubei 430074, China

ARTICLE INFO

Article history:
Received 18 February 2016
Received in revised form 10 March 2016
Accepted 16 March 2016
Available online 19 March 2016

Keywords:
Ground-roll noise
Effective waves
Radon transform
Time–offset domain
Frequency–velocity domain

ABSTRACT

Ground-roll is a main type of strong noises in petroleum seismic exploration. Suppression of this kind of noise is essential to improve the signal-to-noise ratio of seismic data. In the time–offset (t–x) domain, the ground-roll noise and the effective waves (e.g., direct waves, reflections) overlap with each other in terms of time and frequency, which make it difficult to suppress ground roll noise in exploration seismic data. However, significant different features shown in the frequency–velocity (f–v) domain make it possible to separate ground roll noise and effective waves effectively. We propose a novel method to separate them using high-resolution linear Radon transform (LRT). Amplitude and phase information is preserved during the proposed quasi-reversible transformation. The reversibility and linearity of LRT provide a foundation for ground-roll noise suppression in the f–v domain. We extract the energy of ground-roll noise in the f–v domain, and transform the extracted part back to the t–x domain to obtain the ground-roll noise shot gather. Finally, the extracted ground-roll noise is subtracted from the original data arithmetically. Theoretical tests and a real world example have been implemented to illustrate that the ground-roll noise suppression can be achieved with negligible distortion of the effective signals. When compared with the adaptive ground-roll attenuation method and the K–L transform method, the real world example shows the superiority of our method in suppressing the ground-roll noise and preserving the amplitude and phase information of effective waves.

1. Introduction

Ground-roll, the vertical component of Rayleigh wave, is a secondary wave that travels along the free surface, such as the earth–air interface or the earth–water interface. It has the significant characteristics of relatively low velocity, low frequency, high amplitude and strong energy (Sheriff, 2002).

In engineering and environment geophysical exploration, ground-roll (Rayleigh wave) is regarded as a kind of effective wave. Multichannel Analysis of Surface Wave (MASW) method utilizes a multichannel recording system to obtain wide-band, high-frequency Rayleigh waves. Near-surface shear (S)-wave velocity that is a key consideration in construction design engineering can be inverted from high-frequency Rayleigh waves (Xia et al., 1999, 2003, 2006a, 2012b; Zeng et al., 2011a).

Ground-roll, however, is one of the main coherent noises in petroleum seismic exploration. Because of its higher level of amplitude and stronger energy compared to reflection signals, ground-roll noise may mask the shallow reflections at near offsets and deep reflections at far offsets and also distorts reflections by overlapping with them (McMechan and Sun, 1991; Henley, 2003; Halliday et al., 2015). During data acquisition, ground-roll noise can be suppressed by using proper receiver array design and filtering method (Holzman, 1963; Shieh and Herrmann, 1990). Unfortunately, the effective signals of the overlapped frequency bands could be damaged when ground-roll noise is suppressed. It would result in an unacceptable deterioration of reflections (Coruh and Costain, 1983).

Conventional methods for ground-roll noise suppression can be divided into two groups. The first one can be summarized to filter method which is based on suppression of undesired parts of recorded data in the spectral domain, including high-pass and band-pass filtering, f–k filtering (Embree et al., 1963; Treitel et al., 1967; Yilmaz, 2001) and the adaptive ground-roll attenuation method (Hosseini et al., 2015; Wang et al., 2012). However, high-pass and band-pass filter may eliminate the low frequency component of effective waves since the frequency bands of ground-roll noise and reflections are often overlapped. The conventional f–k filter would cause serious distortion of effective waves when the energy of ground-roll noise is much stronger than that of reflections (Liu, 1999; Benoliel et al., 1987; Tokeshi et al., 2006). So the key of filter method lies in the separation of the frequency bands of ground-roll noise and reflections in the spectral domain. The other one is wave field separation method based on ground-roll noise extraction and arithmetical subtraction of it from the raw shot gather in the t–x domain, including Wiener–

* Corresponding author at: Hubei Subsurface Multi-scale Imaging Key Laboratory, China University of Geosciences, 388 Rumo Rd., Wuhan, Hubei 430074, China.
E-mail address: liminwang_1983@126.com (L. Wang).

http://dx.doi.org/10.1016/j.jappgeo.2016.03.007
0926-9851/

Levinson algorithm (Karslı and Bayrak, 2004), Karhunen–Loève (K–L) transform (Liu, 1999; Jones and Levy, 1987; Gómez Londoño et al., 2005), wavelet transform (Deighan and Watts, 1997) and Radon transform (Russell et al., 1990a, 1990b). They were developed either on the frequency or the apparent velocity characteristics of ground-roll noise. With only one single characteristic of signals is focused, however, the effective waves would be unavoidably damaged in some degree.

The high-resolution linear Radon transform (LRT) has been advocated for wave field separation for many years (Foster and Mosher, 1992; Trad et al., 2002, 2003; Nowak and Imhof, 2006; Thorson, 1985). Luo et al. (2008, 2009) utilized high-resolution LRT to image the Rayleigh-wave dispersive energy and separate the multi-mode dispersive Rayleigh-wave energy. It has been demonstrated that high-resolution LRT method is able to achieve much higher resolution of dispersion energy in the frequency–velocity (f–v) domain than other algorithms (Luo et al., 2008). Being different from the conventional Radon transform and the other ones, the raw data is transformed into the f–v domain but not the conventional intercept–slowness (τ–p) domain (Zhou and Greenhalgh, 1994; Russell et al., 1990a, 1990b; Nowak and Imhof, 2006). Besides, high-resolution LRT is a quasi-reversible transformation, and the amplitude and phase information would be effectively preserved using high-resolution forward and inverse LRT. This preservation provides a foundation for the separation of multi-mode Rayleigh waves and suppression of ground-roll noise.

In this paper, we proposed a novel method to extract and suppress the ground-roll noise from a common-shot gather using high-resolution LRT method. We first introduce high-resolution LRT and demonstrate the amplitude and phase preservation of high-resolution LRT. Then we describe different representations of ground-roll noise and reflections in the f–v domain and the process of ground-roll noise extraction and suppression. Theoretical and real-world examples have been used to illustrate the effectiveness of the proposed method When compared with the adaptive ground-roll attenuation method and the K–L transform method, the proposed method produces more accurate result in ground-roll noise suppression with much less distortion of the effective signals.

2. Methodology

2.1. High-resolution LRT

The forward LRT from the time–offset (t–x) domain to the intercept–slowness (τ–p) domain can be achieved by summing over amplitudes along linear trajectories

$$m(p,\tau)=\sum_{x_{\min}}^{x_{\max}} d(x,t=\tau+px), \qquad (1)$$

where $d(x, t)$ denotes the shot gather (recorded data), x is the offset between source and receivers, and t is the time,. $m(p, \tau)$ is the Radon panel with p denotes the discrete slowness and τ denotes the zero offset intercept time (Yilmaz, 2001).

Similarly, the conjugate transform from the intercept–slowness (τ–p) domain to the time–offset (t–x) domain involves summing along the slowness

$$d(x,t)=\sum_{p_{\min}}^{p_{\max}} m(p,\tau=t-px), \qquad (2)$$

After taking a temporal Fourier transformation, the LRT can be calculated for each temporal frequency component f. In matrix notation, they can be written as follows,

$$\mathrm{d} = \mathrm{Lm}, \qquad (3)$$

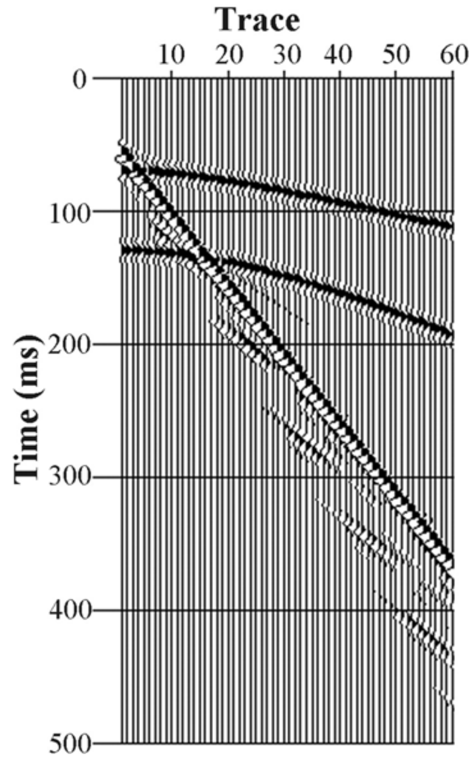

Fig. 1. A synthetic data containing mostly representative ground-roll and additional reflection events.

Similarly, the adjoint transformation can be written as

$$\mathrm{m}_{adj} = \mathrm{L}^{T}\mathrm{d}, \qquad (4)$$

In Eq. (3), $\mathrm{L}=\mathbf{e}^{i2\pi fpx}$ is the forward LRT operator. Based on the matrix theory, as L is not a unitary operator and L^T does not define the inverse operator, m_{adj} denotes a low resolution Radon panel using the transpose or adjoint operator L^T. In order to obtain better resolution in the Radon panel, we first define an objective function. The inverse LRT operator can be found by minimizing the following objective function (Trad et al., 2002, 2003).

$$J=\left\|\mathrm{W_d}\left(\mathrm{d}-\mathrm{L}\mathrm{W_m^{-1}}\ \mathrm{W_m m}\right)\right\|^2+\lambda\|\mathrm{W_m m}\|^2, \qquad (5)$$

In Eq. (5), $\mathrm{W_d}$ is a matrix of diagonal weights, $\mathrm{W_m}$ is a matrix of model space weights that plays an extremely important role in the resolution and smoothness and λ maintains balance between data misfit and model constraints. The minimization of the objective function J can be achieved by solving the following equation using a conjugate gradient (CG) algorithm. More details can be found in many articles (Sacchi and Ulrych, 1995; Sacchi and Porsani, 1999; Herrmann et al., 2000; Trad et al., 2002, 2003; Ji, 2006).

$$\left(\mathrm{W_m^{-T}L^TW_d^TW_dLW_m^{-1}}+\lambda\mathrm{I}\right)\mathrm{W_m m}=\mathrm{W_m^{-T}L^TW_d^TW_d d}, \qquad (6)$$

where I denotes the identity matrix, the weighting and the preconditioning matrices $\mathrm{W_d}$ and $\mathrm{W_m}$ at the ith iteration of the CG algorithm are

Table 1
Parameters of a two-layer model.

Layer number	Vp (m/s)	Vs (m/s)	Density (kg/m^3)	Thickness (m)
1	800	200	2000	5
2	1200	400	2000	Infinite