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Inversion-based directional deconvolution to remove the effect of a geophone array on seismic signal

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ABSTRACT

The geophone array, as a directivity filter, has been widely used in seismic data acquisition for suppressing noises and alias-free sampling, and its negative effects have long been recognized by analyzing its response to harmonic waves. We extended the analysis by considering its effects on seismic signals, especially on amplitude variation with offset (AVO). Taking the ratio of the array length to the dominant wavelength as a reference, we analyzed the attenuations of the peak amplitude and the peak frequency with the incident angle for the Ricker wavelet. When an array with a ratio of 1.0 is used, the peak amplitude and the peak frequency decay to around 50% and 80% respectively at an angle of 40°. The effect of an array is directivity-dependent, and it acts on the seismic record as a nonstationary filter. We present an inversion-based solution to remove the directional effects. On the approximation of the horizontal stratified medium, the horizontal velocity of the seismic reflection can be concisely expressed in terms of its reflection time, offset, and rms velocity, which facilitates the implementation of directional deconvolution. The method was tested using model-based and logging-based synthetic data.

1. Introduction

The geophone array has been widely used in seismic surveys for suppressing noise and alias-free sampling. A group of geophones are deployed according to an assigned spatial pattern and their outputs are summed to generate a seismic trace. A geophone array can be treated as a wavenumber filter with a pass band for long-wavelength waves and a reject band for short-wavelength waves. The underlying principle of a geophone array is that the desired seismic signals travel across the array with a much higher horizontal velocity, and hence a longer wavelength, than that of unwanted types of noise such as ground roll and air blast (Hoffe et al., 2002). Thus, a geophone array can also be considered as a directional filter.

To achieve the best trade-off between noise attenuation and signal preservation, an "optimum" array, with maximum attenuation in the reject band and minimum attenuation in the pass band, should be designed by choosing the spatial pattern and weighting gain (Savit et al., 1958; Holzman, 1963; Schoenberger, 1970). The performance of an array is usually degraded by a number of field factors, such as positioning error, coupling variation, and the effect of local heterogeneity in the field environment. Thus, the array responses that are achieved in fact differ, perhaps considerably, from the nominal responses designed according to idealized conditions (Aldridge, 1989). The more complex array designs are often less tolerant of errors, and must be implemented with greater care and precision in the field (Newman and Mahoney, 1973). Therefore, taking the accuracy, stability, tolerance and cost into consideration, the uniform array, both in spatial distribution and weighting gain, has been the most widely used pattern (Kerekes, 2001).

The wavenumber filter of a geophone array is different from the $f-k$ fan filter in that it is independent of frequency, incapable of passing or rejecting all frequency components of a seismic wave according to its apparent velocity. Hence, the use of an array as the wavenumber filter is always a compromise (Ongkiehong and Askin, 1988). An array whose first rejection notch is assigned to a specific horizontal wavenumber, designed perhaps for reference frequency and angle, may also lead to considerable attenuation of the reflection signals at higher frequencies and angles. In view of its negative effect on seismic signals, some geophysicists became suspicious of the need for a geophone array (Criss et al., 2005) and suggested "point source, point receiver" in seismic acquisition. However, a great number of filed evaluations seemed more favorable toward a geophone array than a single geophone or potted geophones (Kerekes, 2001; Cooper, 2002; Dean et al., 2015).

Apart from the geophone array, the source array also has a directional effect on seismic reflections that can be conceptually equivalent to that of a geophone array. The air-gun array has been widely used in marine seismic surveying; its signature has strong directivity (Hustedt and Clark, 1999). Many efforts have been made to remove signature directivity by the so-called directional designature (Brummitt, 1989; Roberts and Goulty, 1990), the scheme of plane-wave decomposition being commonly used. The receiver gather is transformed from $x-t$ domain to $\tau-p$ or $f-k$ domain, where the take-off angle can be determined, so that the angularly dependent filter can be applied. Van der Schans and Ziolkowski (1983) implemented the directional designature

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in $\tau-p$ domain and Hubbard et al. (1984) also achieved it in $f-k$ domain. Krail and Shin (1990) used the cylindrical $\tau-p$ transform to correct for signature directivity that resulted from the source ghost by taking the source as a vertical dipole of finite length. Special attention must be paid to aliasing, windowing, and interpolation problems to ensure reliable performance when plane-wave decomposition is used (Van der Schans and Ziolkowski, 1983). Additionally, as plane-wave decomposition is a weighted sum of traces from different shots, this approach is only strictly valid if the signatures do not change from shot to shot. Poole et al. (2013) proposed a global directional designature to address the signature variation from shot to shot by using an improved $\tau-p$ transform. To avoid these problems involving the transforms, Lee et al. (2014) estimated directivity directly from the source ghost-delay time and then applied the directional filters in the shot gather.

In this paper, we have proposed an inversion-based directional deconvolution by considering the directional effect as a nonstationary filtering process, and implemented it on the assumption of the horizontally stratified medium. The paper is organized as follows. First, the basics of a geophone array are reviewed, followed by analysis of its effects on seismic signals, especially on amplitude variation versus offset (AVO). Then we present an inversion-based solution to remove the directional effects. The model-based and logging-based synthetic data are used to examine the performance of the method that we have proposed.

2. The effect of a geophone array on seismic signals

2.1. Array response

Vermeer (1990) described the action of a geophone array as two steps: (1) sampling the continuous wavefield and (2) adding the samples (weighted or not) to form one output sample. The response of an array with N elements, uniformly spaced and weighted, can be treated as the response of a discretely sampled boxcar, expressed as

$$p(k) = \frac{\sin N\pi k\Delta x}{N\sin\pi k\Delta x}, \tag{1}$$

where Δx is the element interval and k is the wavenumber. With the element number increasing infinitely, the array response approaches the Fourier transform of a continuous boxcar, expressed as

$$p(k) = \frac{\sin\pi k\Delta d}{\pi k\Delta d}, \tag{2}$$

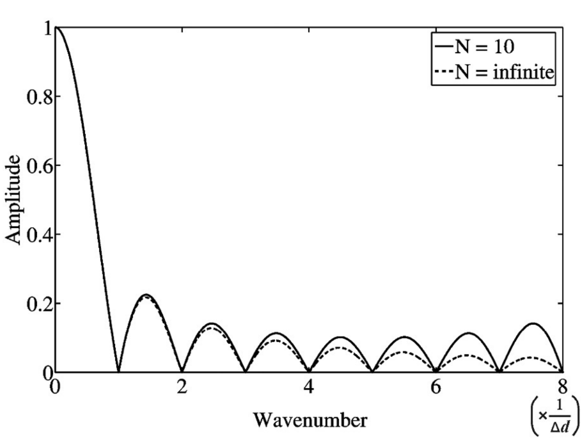

Fig. 1. The array response when the element number is $N=10$ (solid), together with that when $N=\infty$ (dotted). The array response is mainly dependent on the array length Δd and less dependent on the element number when $N\geq 10$.

where Δd is the array length. Fig. 1 shows the array responses when $N=10$ and $N=\infty$. They are very close to each other, and the improvement is not appreciable when the element number is above 10 (Savit et al., 1958). It can be seen from Fig. 1 that there are a series of rejection notches at wavenumber $k=i/\Delta$d, where i is a nonzero integer, and that the primary lobe around $k=0$ forms the passband whose width is determined by the first notch (Hoffe et al., 2002).

2.2. Directional effect on seismic signals

The array effects have been analyzed by many authors (Parr and Mayne, 1955; Carlini and Mazzott, 1989); these analyses are primarily focused on the frequency response of an array and its effect on harmonic waves. As a directional filter, a geophone array unavoidably has effects on the seismic signal itself, such as variations of the amplitude and frequency with offset. Gangi and Benson (1989) analyzed the effect of an array on the reflection amplitude in terms of the travel time across the array, which implied an effect on AVO because the travel time is dependent on the incident angle. Vermeer (2002) demonstrated the effect of an array on harmonic waves traveling at different angles. In his experiment, the group interval was defined according to the anti-aliasing requirement as

$$\Delta r = v/(2f_{\max}\sin\theta_{\max}), \tag{3}$$

where $\theta_{\max}$ is the maximum angle of interest, $f_{\max}$ is the highest effective frequency and v is the interval velocity. When the length of an array is 50% larger than the group interval, the array can produce a dramatic loss at high frequencies, and this may have a detrimental effect on the signal amplitude (Vermeer, 2002).

We take the Ricker wavelet as the reflection signal to demonstrate the effect of an array on variations of the peak amplitude and the peak frequency with incident angle. For a Ricker wavelet $w(t)$ with peak frequency f_p, its dominant period should be $T_d=1/(1.3f_p)$ according to Kallweit and Wood (1982). Defining the ratio γ of the array length Δl to the domain wavelength λ_d as

$$\gamma = \frac{\Delta l}{\lambda_d}. \tag{4}$$

The geophone interval of an array with N geophones spaced uniformly is

$$\Delta x = \frac{\Delta l}{N-1} = \frac{\gamma\lambda_d}{N-1}. \tag{5}$$

For the waves arriving at the array with angle α and velocity v, the time difference between adjacent geophones is

$$\Delta t = \frac{\Delta x\sin\alpha}{v} = \frac{\gamma\lambda_d\sin\alpha}{vN-1} = \frac{\gamma T_d\sin\alpha}{N-1}. \tag{6}$$

Thus, the output of an array can be expressed in terms of the angle as

$$s(\alpha,t) = \frac{1}{N}\sum_{i=0}^{N-1} w(t-i\Delta t) = \frac{1}{N}\sum_{i=0}^{N-1} w\left(t-i\frac{\gamma T_d\sin\alpha}{N-1}\right). \tag{7}$$

Fig. 2a shows the peak amplitude attenuation versus the incident angle for a 12-element array when $\gamma=0.5$, $\gamma=1.0$, and $\gamma=1.5$, respectively. With the ratio increasing, the array imposes stronger attenuation on the signals. The array length is normally set as equal to the group interval, and the group interval is theoretically chosen according to the anti-aliasing requirement expressed in Eq. (3). Taking a reasonable example in which the dominant frequency is 50 Hz, the interval velocity is 2500 m/s, the maximum angle of interest is 30°, and the highest frequency is twice the dominant frequency, the dominant wavelength is then 50 m; the array length, equal to the group interval derived