INVERSION BASED DATA-DRIVEN ATTENUATION COMPENSATION METHOD

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ABSTRACT

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Seismic data resolution can be reduced because of heterogeneity and viscosity of subsurface medium. Inverse Q-filtering and Gabor deconvolution are able to effectively improve seismic data resolution. However inverse Q-filtering requires accurate Q values and it is always unstable or under-corrected for amplitude compensation, while Gabor deconvolution is based on the assumption of a minimum phase wavelet, which deviates from real conditions to some extent, therefore its application is limited. This paper combines merits of inverse Q-filtering and Gabor deconvolution: neglecting effects of wavelet and just compensating attenuation. The procedures include: 1) Extract an attenuation function by hyperbolic smoothing in Gabor domain; 2) Use non-combination theory and inverse strategy to restore effective frequency components of the compensated seismic data; 3) Perform an inverse Fourier transform to obtain compensated seismic data. This method, does not need an accurate Q value, is stable and accurate compared with traditional inverse Q-filtering methods; it is data driven and is applicable to different data sets because it avoids the assumption of a minimum phase wavelet compared with Gabor deconvolution; it is computationally efficient because only the effective frequency components are calculated compared with methods that need to calculate the whole seismic data series. The validity of the proposed method has been verified by tests on synthetic and real data.

KEY WORDS: inverse Q-filtering method, Gabor deconvolution, attenuation compensation, data-driven, non-stationary combination.

INTRODUCTION

When seismic waves propagate in the subsurface media, there is a forward Q effect because of heterogeneity and viscosity of the subsurface medium. This attenuates the amplitude and distorts the phase, leading to decreased resolution in the seismic data (Futterman, 1962). High resolution seismic data, which is required by accurate reservoir description and for seismic data interpretation, can be achieved through attenuation compensation methods (van der Baan, 2012).

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Inverse Q-filtering is one of the effective attenuation compensation methods, which is stable and robust for phase correction while the amplitude compensation factor increases exponentially as time and frequency increase, leading to instability and noise sensitivity (Wang 2002,2003,2006; Zhang, 2007). Hargreaves and Calvert (1991) developed a fast inverse Q method which is akin to Stolt's wavenumber-frequency domain migration and can correct phase distortion from velocity dispersion but amplitude compensation is neglected because of its instability. Due to the instability of amplitude compensation, Wang (2002,2003,2006) developed an amplitude gain-limited method and stabilized inverse Q method that can compensate the amplitude and correct the phase distortion simultaneously; An attenuation compensation algorithm in the Gabor domain is developed to improve efficiency. When dealing with noisy seismic data, the amplitude gain-limited method amplifies too much the noise level, leading to instability; while the stabilized inverse Q method can correct the phase distortion effectively, the amplitude is under compensated. Yan and Liu (2009) applied a stabilized inverse Q-filtering method to multi-component seismic data: shear wave Q values and primary wave Q values are extracted from pre-stack converted wave gathers and primary gathers respectively, achieving compensated pre-stack converted PS waves and PP waves whose resolution is improved significantly. Zhao et al. (2012) developed a time-frequency method which defines the S/N ratio in the time-frequency domain and compensates the data whose S/N is greater than 1. This method improves the seismic data resolution while not amplifying the noise level. However all these methods need Q values as a prerequisite, and in order to weaken the dependence on Q values, Braga and Morales (2013) implemented inverse Q-filtering in the wavelet domain.

Due to instability or under-compensation of the amplitude compensation in the inverse Q method, Zhang and Ulrych (2007) inverted the sparse reflectivity series iteratively based on a least square error strategy and Bayes' theorem, while still requiring Q values to correct phase distortion and the known wavelet, or to extract a minimum phase wavelet from the seismic trace in order to achieve the sparse reflectivity series. Wang (2011) developed a forward Q-filtering formula which is based on the exploding reflector model and Futterman's attenuation model. Using regularization strategy and inverse theory, compensated seismic data can be obtained by this method that avoids instability or under compensation to some extent compared with traditional inverse Q methods, but it still requires accurate Q values.

Margrave et al. (2003) generalized Wiener deconvolution, and developed the Gabor deconvolution strategy; Margrave et al. (2011) estimated attenuation spectrum and wavelet spectrum through hyperbolic smoothing over the Gabor spectrum of seismic data, assuming that the spectrum of the reflectivity series is white. Under the minimum phase assumption, an attenuation function and wavelet can be achieved, then a high resolution reflectivity series may be obtained. Reine et al. (2009) analyzed the robustness of seismic attenuation measurements using fixed and variable-window time-frequency transforms. A variable-window time-frequency transform can reduce the uncertainty and bias of the resulting attenuation estimate, resulting in higher precision.

Smoothing methods belong to the category of statistical methods and different hyperbolic smoothing methods can lead to different accuracies in attenuation spectrum estimation. Margrave et al. (2011) divided $tf_{max} = t_{max}f_{max}$ into equal parts and obtain many hyperbolic stripes. When the number of division is low, under sampling in the lower valued tf domain results in a larger estimation error for attenuation function; increasing the division number can reduce the estimation error but weakens its statistical reliability. In order to overcome those defects, Li et al. (2013) developed hyperbolic smoothing with a variable-step sampling method that can achieve a high accuracy attenuation spectrum when the division number is small, while keeping statistical reliability. Wu et al. (2011) and Sun et al. (2012) developed methods that estimate the attenuation spectrum in the logarithmic spectrum using hyperbolic smoothing.

This paper combines the advantages of inverse Q-filtering, which neglects the effect of the wavelet and just compensates attenuation, and that of Gabor deconvolution method, which estimates the attenuation function through a hyperbolic smoothing method in the Gabor domain. The procedures include: 1) Extract the attenuation function by hyperbolic smoothing method in the Gabor domain; 2) Use non-combination theory and an inverse strategy to restore the effective frequency components of the compensated seismic data; 3) Perform an inverse Fourier transform to obtain compensated seismic data. This method, which does not need an accurate Q value, is stable and accurate compared with traditional inverse Q methods; it is data driven and can be applied to different data sets because it avoids the assumption of a minimum phase wavelet compared to the Gabor deconvolution; it is also computationally efficient because only the effective frequency components are calculated compared with methods that need to calculate the whole seismic data series. Tests on synthetic and real data confirm the validity of the proposed method.

METHOD

Non-stationary combination theory

Non-stationary combination formula in the mixed domain(Margrave, 1998) is as follows,

$$s(\tau) = \int \alpha(f,\tau)S(f)e^{i2\pi f\tau}df \quad , \tag{1}$$

where $s(\tau)$ is the attenuated seismic data, $\alpha(f,\tau)$ is a complex valued attenuation function, S(f) is the spectrum of the original seismic data without attenuation, $e^{i2\pi f\tau}$ is the kernel of inverse Fourier transform. According to Gabor deconvolution (Margrave et al., 2011), attenuation spectrum can be estimated through hyperbolic smoothing over the Gabor spectrum of the attenuated seismic data. The Gabor spectrum of the attenuated seismic data can be divided into three parts, attenuation spectrum, spectrum of the stationary wavelet and the spectrum of the reflectivity, shown as eq. (2),

$$S_1(f,\tau) = \alpha(f,\tau)W(f)R(f,\tau) \quad , \tag{2}$$

where $S_1(f,\tau)$, $\alpha(f,\tau)$, W(f) and $R(f,\tau)$ are Gabor spectra of the attenuated seismic data, the attenuation function, the stationary wavelet and the reflectivity series, respectively. The attenuation function can be estimated through hyperbolic smoothing over the Gabor spectrum of the attenuated seismic data, under the minimum phase assumption for the attenuation function. Inserting the attenuation function into eq. (1), we can restore the effective frequency components of the compensated seismic data. The compensated seismic data can be retrieved easily through an inverse Fourier transform.

Rewriting eq. (1) in matrix form,

$$s = \mathrm{Re}(\mathbf{\Phi}S) \quad , \tag{3}$$

where **s** is the attenuated seismic data (real valued vector), $\mathbf{\Phi}$ is the complex valued matrix that contains information about attenuation and the inverse Fourier transform, S is the effective frequency components of the compensated seismic data (complex valued vector). Transforming eq. (3) into a real valued equation,

$$\mathbf{d} = \mathrm{Lm} \quad , \tag{4}$$

where, $\mathbf{d} = \mathbf{s}$, $L = [\mathrm{Re}(\mathbf{\Phi}), -\mathrm{Im}(\mathbf{\Phi})]$, $m = [\mathrm{Re}(S);\mathrm{Im}(S)]$. Because of the limitation of observed seismic data sets, band-limited seismic data and the effect of noise, eq. (4) is ill-posed. Due to the smoothness of seismic data spectrum, the functional is constructed as follows after adding smoothing constraints,

$$C(m) = \| Lm - d \|^2 + \mu \| Dm \|^2 \quad , \tag{5}$$

where μ is the regularization factor, and D is the differential operator that can choose a unit operator, a first order differential operator or a second order differential operator. The normal equation can be obtained through differentiation with respect to m in eq. (5),

$$(L^TL + \mu D^TD)m = L^Td \quad . \tag{6}$$

Effective frequency components of the compensated seismic data can be obtained by solving formula (6). Then the compensated seismic data is achieved through an inverse Fourier transform. However, the complex valued attenuation function $\alpha(f,\tau)$ is always unknown, and how to get the accurate attenuation function is the key to attenuation compensation problems.

Estimation of the attenuation function

The theoretical formula of the attenuation function is as follows,

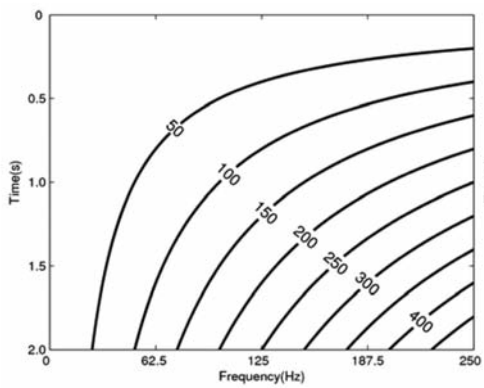
$$\alpha(f,\tau) = e^{-(\pi f\tau/Q)+iH(\pi f\tau/Q)} \quad , \tag{7}$$

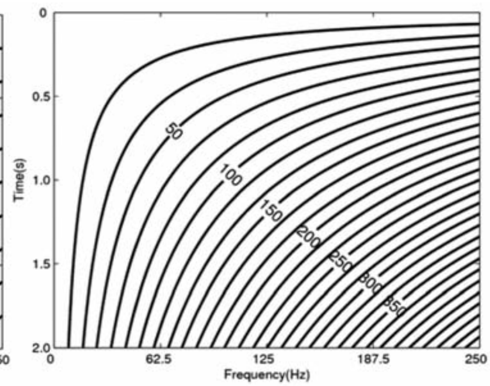
where Q is the quality factor, H(•) is the Hilbert transform along the frequency axis with the assumption of minimum phase. If the Q value is known, the attenuation formula has an analytical form, but the accurate estimation of the Q value is extremely difficult and its error will affect the precision of attenuation compensation or even lead to deviation from real conditions. Therefore, estimating the attenuation function directly can improve the precision of the attenuation compensation.

According to the theoretical formula (7) of the attenuation function, attenuation equates to the hyperbolic curve of $\tau f = C$, so the spectrum of the attenuation function can be estimated through hyperbolic smoothing over the Gabor spectrum of the attenuated seismic data with the assumption of a white reflectivity series. Under the assumption of minimum phase, phase information can be obtained through the Hilbert transform; then effective frequency components of the compensated seismic data can be obtained by solving formula (6); finally, compensated seismic data can be obtained through an inverse Fourier transform. The algorithm is efficient and can reduce the effect of high frequency noise to some extent compared with methods that solve the whole frequency band of seismic data.

Different hyperbolic smoothing methods can result in estimated attenuation functions of different accuracy. The traditional hyperbolic smoothing method (Margrave et al., 2011) divides the whole domain into hyperbolic strips, bounded by $\tau f_i = (i - 1)d\tau f$, $i = 2,\ldots,N+1$, $\tau f_1 = 0$, $d\tau f = \tau f\max/N$, shown as Fig. 1.

Fig. 1(a) shows that the division method is under sampling in the lower valued τf domain while the energy of seismic signal mainly focuses in this domain. This under sampling may lead to an estimated attenuation function with low accuracy. Increasing the division number can improve the precision to some extent with the cost of weakening the statistical reliability because there are fewer points in each strip, as shown in Fig. 1(b).





(a) (b)

Fig. 1. Bin division by traditional hyperbolic smoothing method (a) N = 10; (b) N = 30.

In order to overcome these defects of traditional hyperbolic smoothing, Li et al. (2013) proposed a variable-step hyperbolic smoothing method. The amplitude spectrum of theoretical attenuation function is $A = \exp(-\pi tf/Q)$, and the value of A lies in (0,1] when tf ranges in [0,tfmax]. Strip boundaries can be determined as $tf_i = -\log[(i-1)dA](Q/\pi)$, $i = 2,3,\ldots$ and $tf_1 = 0$, through dividing the energy intervals into equal parts $dA = 1/N$. We can take a constant as an approximation to the unknown Q value because the estimated attenuation function is insensitive to this Q value. This algorithm divides the tf domain according to its energy distribution and has its physical meaning. This avoids the shortcomings of under sampling in the lower valued tf domain when the division number is small compared with the traditional hyperbolic smoothing method and keeps statistical reliability, as shown in Fig. 2.

After dividing the tf domain into N hyperbolic strips, we can obtain a mean value estimation of the $smooth_k$ and central hyperbolic curve $tflevel_k$ in each strip:

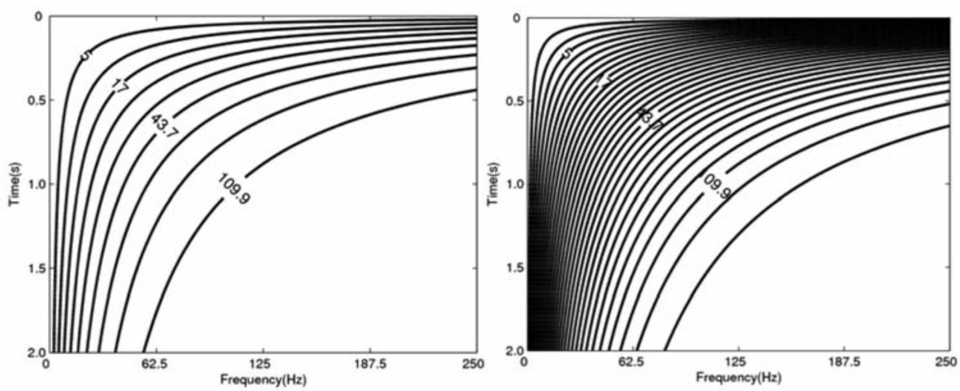
$$smooth_k = \mathrm{mean}\{|S(\tau,f)|,(\tau,f) \in \Omega_k\} \ ,$$

$$tflevel_k = 0.5(tf_k + tf_{k+1}) \ ,$$

where Ω_k is the k-th hyperbolic strip.

Assuming that a (t,f) point lies in the interval $[tflevel_k, tflevel_{k+1}]$ where $tflevel_k$ is the center of the k-th hyperbolic strip, whose spectrum has been obtained through hyperbolic smoothing in the latest step, then the spectrum in the (t,f) point can be calculated through interpolation,

$$smooth(\mathrm{tf}) = smooth_{k+1}[(\mathrm{tf} - tflevel_k)/(tflevel_{k+1} - tflevel_k)] + smooth_k[(tflevel_{k+1} - \mathrm{tf})/(tflevel_{k+1} - tflevel_k)] \quad . \quad (8)$$



(a) (b)

Fig. 2. Bin division by variable-step hyperbolic smoothing method (a) N = 10; (b) N = 30.

NUMERICAL EXAMPLES

The proposed method is a single channel processing method. In order to verify the feasibility of this method, firstly, design synthetic seismic data without and with attenuation using zero-phase or minimum phase wavelet and reflectivity series based on non-stationary combination theory; secondly, based on traditional and variable-step hyperbolic smoothing method to estimate attenuation function; finally, using a non-stationary forward formula and inverse theory, we can obtain the compensated seismic data. The consistency of the compensated data with the seismic data without attenuation is judged to verify the validity of this proposed method and then the method is applied in a real case study.

Theoretical model analysis

A Ricker wavelet with a central frequency of 30 Hz, as shown in Fig. 3(a). Its amplitude spectrum is used to generate the corresponding minimum phase wavelet by the Hilbert transform, as shown in Fig. 3(b). Synthetic seismic data and the corresponding compensation results using the proposed method based on zero-phase and minimum-phase wavelets are shown in Figs. 4(a) and 4(b), respectively.

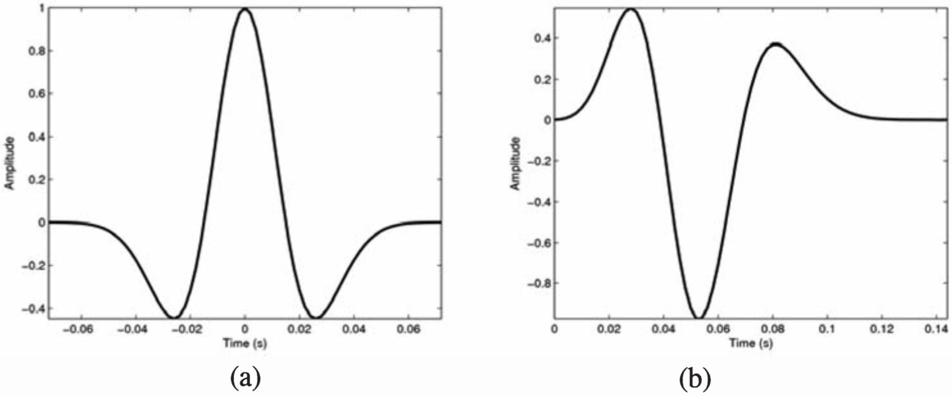


Fig. 3. Theoretical wavelet(a) zero phase (b) minimum phase.

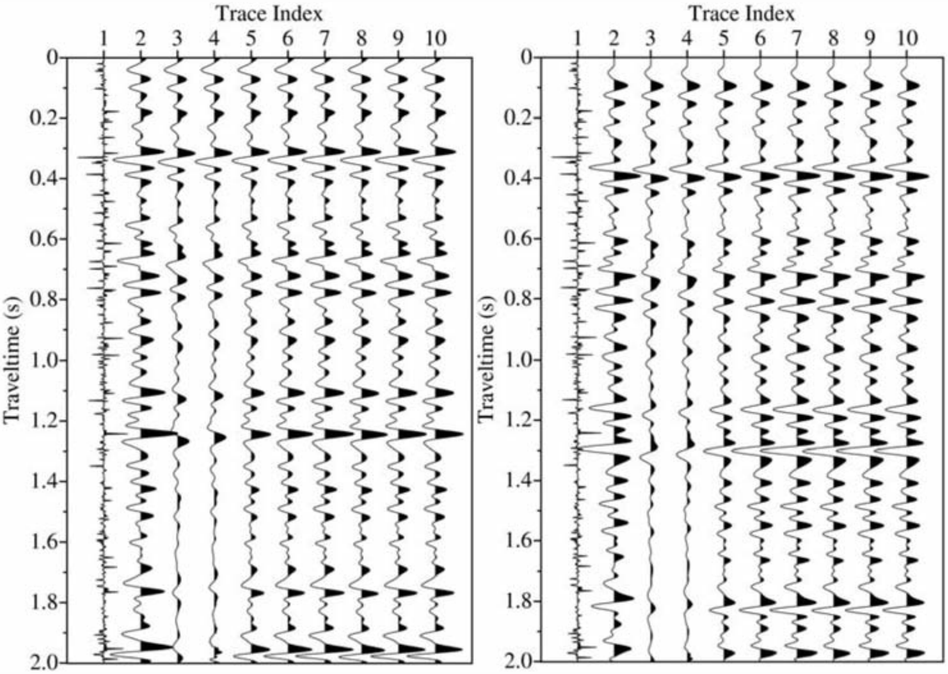


Fig. 4. Synthetic records and the corresponding attenuation compensation results for a zero phase wavelet (a) and a minimum-phase wavelet (b).

Fig. 4(a) shows corresponding results based on a zero-phase wavelet shown in Fig. 3(a). The first trace is the reflectivity series; the second trace is the synthetic seismic data without attenuation based on the non-stationary combination formula (1) (with the quality factor $Q = \infty$); the third trace is the attenuated seismic data based on the non-stationary combination formula (1) (with a quality factor $Q = 50$). The latter indicates that with the increase of travel time, the energy of the wavelet gradually decreases and the losses of high frequency are relatively serious. The theoretical attenuation function spectrum is shown in Fig. 5, indicating that with the increase of time and frequency, the attenuation becomes more and more serious.

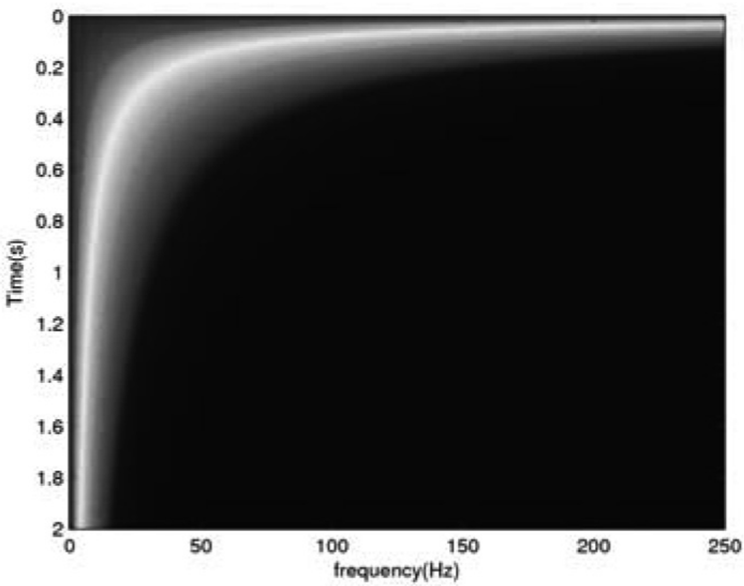


Fig. 5. Theoretical spectrum of the attenuation function.

Performing a Gabor time-frequency transform over the attenuated seismic records, i.e., the third trace of Fig. 4(a), we can obtain Gabor spectrum that can be used to estimate the spectrum of the attenuation function by the hyperbolic smoothing method. Phase information can be estimated through the Hilbert transform under the assumption of minimum phase. Based on formula (6), effective frequency components of the compensated seismic data can be restored by inversion; finally, performing an inverse Fourier transform, the compensated seismic data can be obtained. When the partition number is 10, 30, 50 or 100, the estimated attenuation spectrum by the traditional hyperbolic smoothing method is shown in Figs. 6(a) - 6(d), respectively. This shows that with an increase in the partition number, the estimated attenuation spectrum is closer to the theoretical attenuation spectrum (Fig. 5). However, more stripes lead to fewer points in each stripe that will weaken the statistical reliability. The attenuation compensation results corresponding to Figs. 6(a) - 6(d) are shown in 4th-7th traces of Fig. 4 indicating that with an increase in the division number, the accuracy of the attenuation compensation gradually increases. Based on the variable-step hyperbolic smoothing (N = 10), the estimated attenuation spectrum is shown in Fig. 7. In this, the division number is less but it maintains statistical reliability resulting in higher precision of the estimated attenuation spectrum and an improved consistency with the theoretical attenuation model in Fig. 5. When the partition number is 10, 20 or 30, the attenuation compensation results are shown in the 8th-10th traces of Fig. 4, respectively. These all have high precision and excellent consistency with the original seismic records without attenuation. This demonstrates that variable-step hyperbolic smoothing method is not sensitive to the partition number. The 4th-7th traces of Fig. 4 show that the compensation accuracy of the traditional hyperbolic smoothing method (N = 10) is poorer when the partition number is lower, and with increasing partition number, the accuracy of the compensation attenuation gradually increases at the cost of reducing the statistical reliability to some extent; the 8th-10th traces show that the variable-step hyperbolic smoothing method can guarantee the statistical reliability as well as obtaining high precision

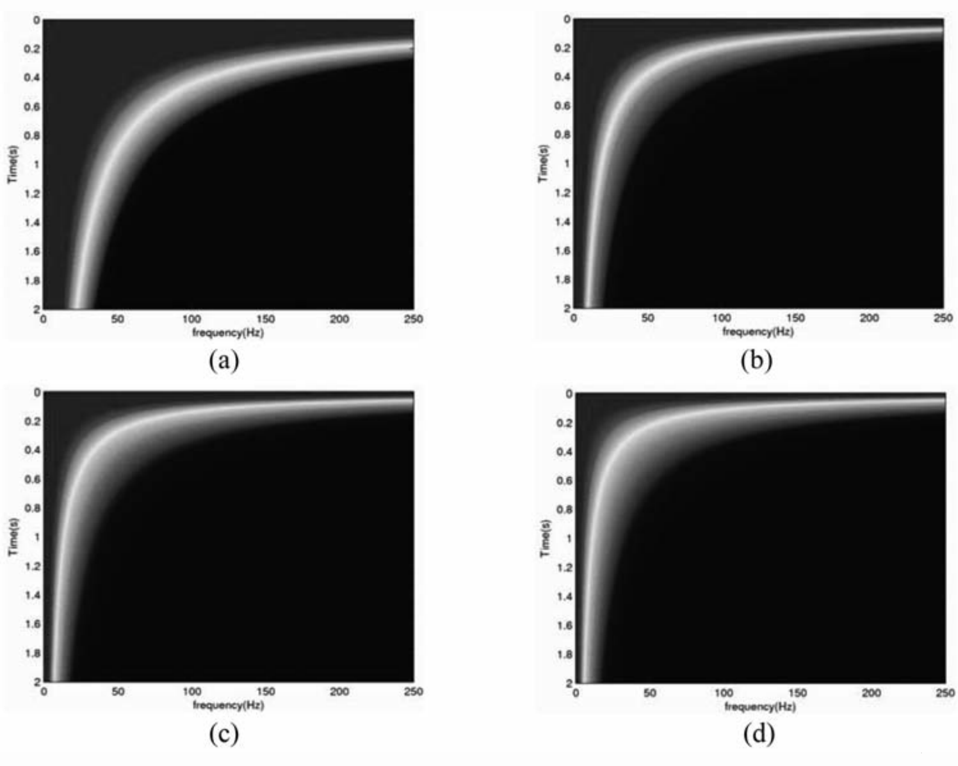


Fig. 6. Estimated attenuation spectrum based on the traditional hyperbolic smoothing according to different division numbers (a) 10, (b) 30, (c) 50, (d) 100.

attenuation compensation results having a good consistency with the original seismic record without attenuation, even when partition number is lower. Tests on the synthetic seismogram with a zero phase wavelet demonstrate the validity of the proposed method and that the variable-step hyperbolic smoothing is more robust.

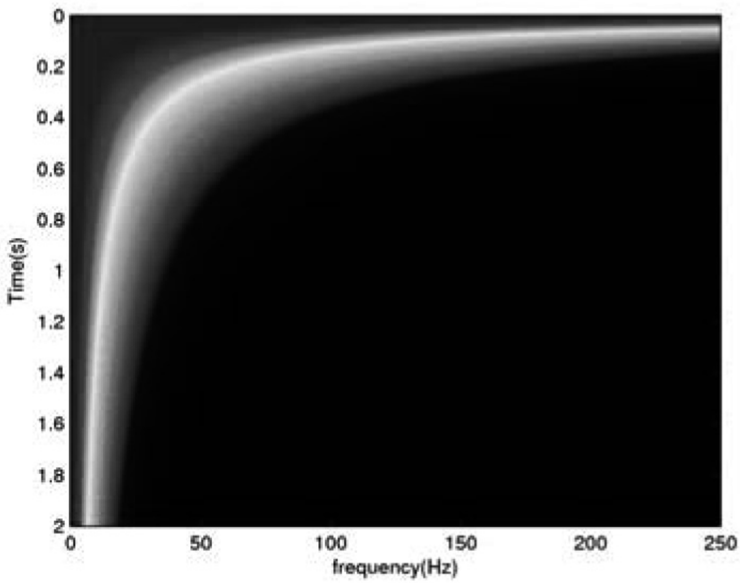


Fig. 7. Estimated attenuation spectrum based on the variable-step hyperbolic smoothing (N = 10).

After applying the traditional hyperbolic smoothing method and the variable-step hyperbolic smoothing method combined with an inversion strategy (the proposed method) to the synthetic seismic record using a minimum phase wavelet, the result is similar to that with the zero phase wavelet synthetic seismogram. The seismograms and the corresponding compensation results are shown in Fig. 4(b); the first trace is the reflection coefficient series; the second trace is the un-attenuated synthetic seismogram with a minimum phase wavelet; the third trace is the seismic record with attenuation by non-stationary combination formula (1) (with Q = 50); the 4th-7th traces are the attenuation compensated seismic records by the traditional hyperbolic smoothing method when the partition number is 10, 30, 50 and 100, respectively; and the 8th-10th traces are the attenuation compensation results by the variable-step hyperbolic smoothing method when the partition number is 10, 20 and 30, respectively. This analysis illustrates that with an increasing partition number, the estimated accuracy can be improved, while fewer sampled points within each stripe will weaken statistical reliability for the traditional hyperbolic smoothing method.

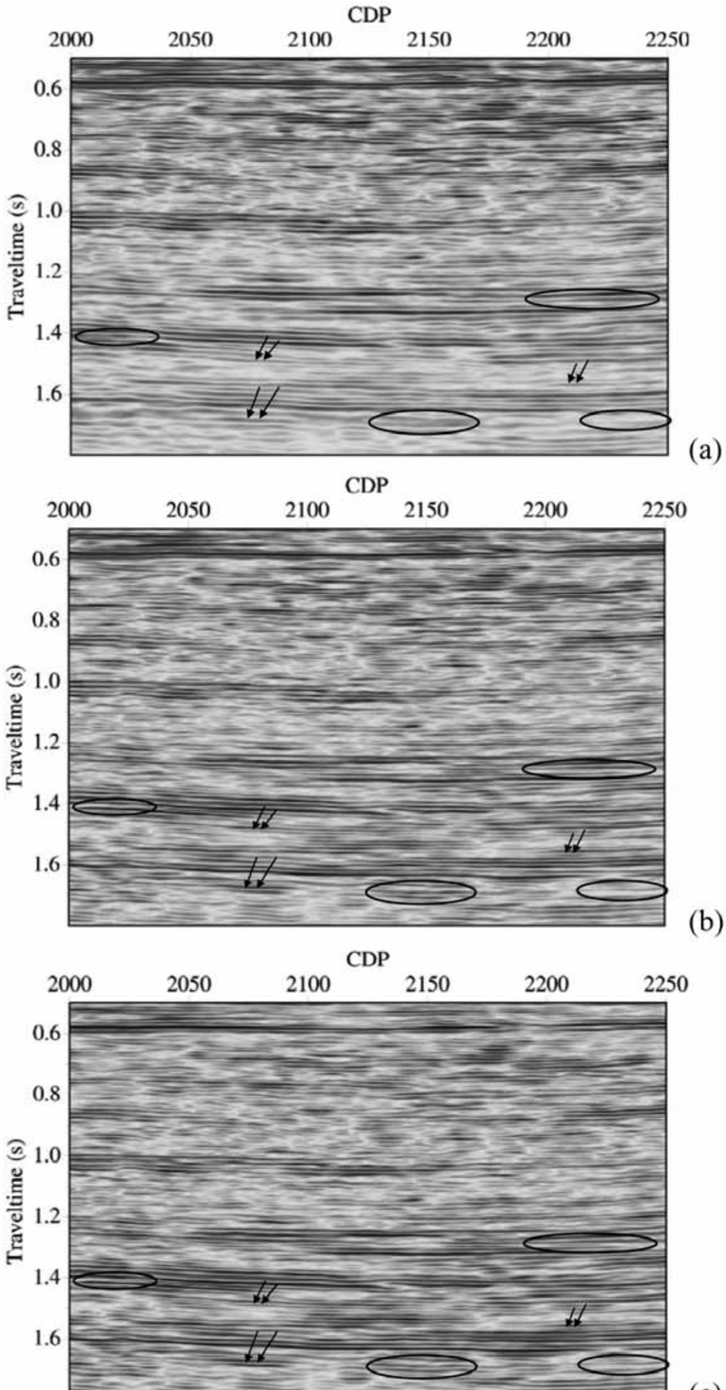


Fig. 8. Real data attenuation compensation before (a); after the traditional hyperbolic smoothing method (b); after the variable-step hyperbolic smoothing method (c).

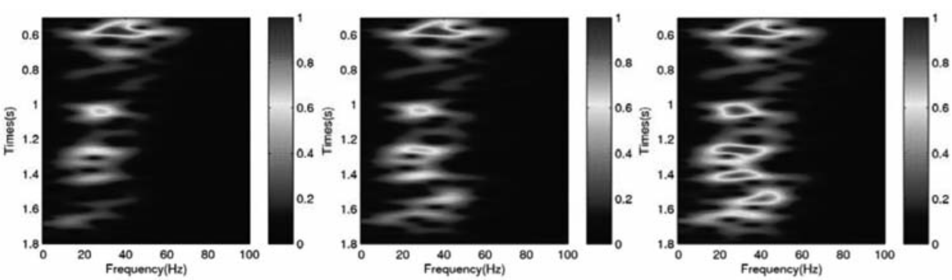
On the other hand, the variable-step hyperbolic smoothing method can guarantee statistical reliability and obtain an estimated attenuation function with high precision with a low partition number. The compensation results through this inversion strategy have a good consistency with the original seismic records without attenuation that verifies the validity of this proposed method and that the variable-step hyperbolic smoothing is more robust than the traditional hyperbolic smoothing.

From the above discussions, the compensated seismic records by inversion based on the variable-step hyperbolic smoothing method have high precision and good consistency with the original seismic records without attenuation. The proposed method only compensates for attenuation effect while not removing the influence of the wavelet and leads itself to a data-driven method that can be adaptive to various field data with wavelets of different phase.

Real data application

Due to heterogeneity and viscosity in the subsurface medium, the amplitude of a seismic wave is attenuated and its phase is distorted as it propagates. It is vital to improve seismic data resolution through attenuation compensation method to enable reliable interpretation of deep strata. The traditional inverse Q methods need a priori knowledge about the Q value and this is always unstable for amplitude compensation; Gabor deconvolution does not need an accurate Q value, but is based on the assumption of a minimum phase wavelet, deviating from the real case to some extent; The proposed method combines the advantages of the Gabor deconvolution method and the inverse Q method, estimating an attenuation function in the Gabor domain and just eliminating the attenuation effect. On the one hand, it ignores the effect of the wavelet and can adapt to different seismic data sets; On the other hand, it is based on inversion plus a regularization strategy and avoids instability or under-compensation characteristic of the traditional inverse Q methods. A synthetic seismic data experiment verified the validity of the proposed method, next application to real seismic data is performed.

Fig. 8(a) shows post-stack seismic data from an oil field. There are 251 traces, 651 sampling points per trace, the time sampling interval is 2 ms, and time range is between 0.5 s and 1.8 s. Fig. 8(a) shows that seismic energy is attenuated and the phase is distorted as the wave propagates through the subsurface, leading to a relatively difficult interpretation of the deep strata. Firstly, using the traditional hyperbolic smoothing method and the variable-step hyperbolic smoothing method (with a partition number of 10) to estimate the attenuation spectrum from the Gabor spectrum of seismic records under the minimum phase assumption, the phase information is obtained by the Hilbert transform. Secondly, based on formula (6), the effective frequency components of the compensated seismic data can be restored. Finally, the compensated seismic data can be obtained by an inverse Fourier transform, as shown in Figs. 8(b) and 8(c). The compensated seismic data has a balanced energy distribution from shallow to deep. The deep seismic events become more continuous and more easily recognized, and the phase distortion is corrected to some extent, all of these infer that the seismic resolution is improved, especially in the places indicated by black arrows and ellipses in the Figs. 8(b) and 8(c). The accuracy of the variable-step hyperbolic smoothing method based on inversion is higher than that of the traditional hyperbolic smoothing method. The normalized average time-frequency spectra before and after compensation are shown in Fig. 9. After compensation, the seismic energy is relatively well balanced from shallow to deep, and the compensation based on the variable-step hyperbolic smoothing method is better. Real data application proves the validity of the proposed method.



(a) (b) (c)

Fig. 9. Time-frequency spectrum before compensation (a); after traditional hyperbolic smoothing method(b); after the variable-step hyperbolic smoothing method.

CONCLUSIONS

Based on a non-stationary seismic model, we design a work flow to improve seismic resolution for better interpretation. Firstly, estimates of the attenuation function from the Gabor spectrum of attenuated seismic data by hyperbolic smoothing method are made. Secondly, non-stationary combination theory is used with a regularization strategy to retrieve the effective frequency components of the compensated seismic data. Thirdly, the inverse Fourier transform is applied to achieve the compensated seismic series. Due to ignoring the wavelet effect, the method is adaptive to seismic data sets with wavelets of arbitrary phase. On the other hand, it is based on inversion and does not require a priori Q value, therefore it has high accuracy. Synthetic seismic data analysis and real data analysis have verified the validity of the proposed method. Several conclusions and suggestions for this research are as follows:

(1) The method ignores the wavelet effect, only enhancing seismic data resolution by attenuation compensation and having no requirements for wavelets. It is adaptive to seismic data sets with wavelets of different phase, overcoming the defects of Gabor deconvolution which is based on the assumption of a minimum phase wavelet.

(2) The method does not require an accurate Q value and the attenuation information can be estimated from the Gabor spectrum of the observed seismic data, overcoming the defect of the traditional inverse Q methods that need a Q value as a prerequisite.

(3) The method is based on an inversion and regularization strategy to achieve the compensated seismic data avoiding the instability or under-compensation for amplitude compensation of traditional inverse Q methods to some extent.

(4) Compared to the traditional hyperbolic smoothing method, the variable-step hyperbolic smoothing method can estimate attenuation function more accurately and compensated seismic data with a higher resolution with a lower partition number.

(5) The defect of the proposed method is that the wavelet effect is not removed. Performing blind deconvolution over the compensated seismic data to estimate a stationary wavelet and a high resolution reflectivity series will be the topic of future research. Another shortcoming is that the proposed method still assumes minimum phase of attenuation function, and errors can occur when calculating phase information from its corresponding amplitude spectrum using the Hilbert transform. How to reduce the effects of this assumption of minimum phase is a research topic for the future.

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