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A new time-varying gain limits inverse Q filtering with the continuous compensation function

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Summary

Inverse Q filtering of seismic data has become a common and useful approach in seismic reservoir characterization for increasing the resolution and preserving the amplitude of seismic data. But the approach is facing the need of improving the resolution with effectively suppressing the noise caused by the different methods. So a lot of work have been carried out for improving the quality of the inverse Q filtering of seismic data and different algorithms have been proposed since the method was firstly proposed in 1981 (Hale, 1981). Recently, the methods proposed by several people (Zhang, 2015; Tim Seher, et. al, 2019) have drawn our attention to develop a new inverse Q filtering method with the stabilizing time-varying inverse Q filter to increase the quality of seismic amplitude compensation for reservoir characterization in one of our research projects.

During the researching of our new method, we mainly studied and compared the current popular inverse Q filtering methods, such as the methods proposed by Wang, Y H (2002), Zhang, G L (2015) and Tim Seher, et, al (2019), and we finally made an important improvement by finding a new method to compute the time-varying gain limits of compensation function based on the smoothing continuous functions instead of based on the piecewise function or cut-off frequency. The new method proposed has the advantages of all current common using methods, such as stabilization and adapted time-varying gain limits in same time, and so on, so it can increase the resolution of seismic data significantly and reach the goal of amplitude preserved of seismic data. Theoretical and field examples have proved the validation of the method proposed, and the results are very encouraging when the method is applied to not only post-stack data but also pre-stack data in the buried-hill basement rock reservoir characterization in the study area of Bohai Bay, in Eastern China.

Theory and Method

Inverse Q filtering is an effective method to compensate the attenuation and dispersion of seismic wave propagated in the subsurface, which is mainly reflected as the distortion of amplitude and the change of the phases in the seismic data due to the viscous effects in the real subsurface strata. In general, the focus of the current inverse Q filtering methods is to get proper compensation function by handling the gain limits of the filter to improve the quality of seismic data with the fine continuity of seismic events and increasing energy of reflections, especially for the deep layers.

The common used method for inverse Q filtering in the time-frequency domain is the so called stabilizing factor method given by Wang (2002) with following basic equation:

$$A(\tau+\Delta\tau,\omega) = A(\tau,\omega)\Phi(\tau,\omega)\times\exp\left(i\left|\frac{\omega}{\omega_0}\right|^{-\frac{1}{\pi Q}}\omega\Delta\tau\right) \quad (1)$$

Where $A(\tau)$, $A(\tau+\Delta\tau)$ and $A(\tau)$ denote the wave field before and after inverse Q filtering at time τ and frequency ω. $\Phi(\tau, \omega)$ is called compensation function with the following expressions:

$$\Phi(\tau,\omega)=\left(\frac{1}{\varphi(\tau,\omega)}+\sigma^2\right)/\left(\frac{1}{\varphi(\tau,\omega)^2}+\sigma^2\right) \tag{2}$$

Where σ is the stabilizing factor, $\varphi(\tau, \omega)$ is conventional amplitude compensation function, and the maximum of amplitude boost is called gain limits defined as

$$c=\Phi(\tau,\omega_s) \tag{3}$$

In Wang's method, the *c* is a fixed value for every layer corresponding to the maximum of the compensation function which can not properly handle the different gain limits of compensation functions for different layers in the data, so the method will show the noise-increasing and bad resolution in the seismic data, especially for deep layer, etc.

Zhang (2015) proposed a method called adapted gain-limit inverse Q filtering method to improve the quality of compensation function, which is based on the Wang's equation with the stabilization factor *σ* as time-varying, and the compensation function is a piecewise function. The expression of compensation function in Zhang's method is as equation (4).

We proposed a new method by deriving a new relationship between the gain limits and formation quality factor Q with a continuous function, so the stabilization factor *σ* in the above equation (2) varied with quality factor Q, and the inverse Q filtering proposed based on the new relationship is the time-varying.

$$\Phi^*(\tau,\omega_m(\tau))=\begin{cases}\varphi(\tau,\omega_m(\tau)) & \omega\geq\omega_m(\tau)\\ 2*\dfrac{\dfrac{1}{\varphi(\tau,\omega_m(\tau))}}{\dfrac{1}{\varphi(\tau,\omega_m(\tau))^2}+\dfrac{1}{c(\tau)^2}} & \omega\geq\omega_m(\tau)\end{cases} \tag{4}$$

Where $\omega_m(\tau)$ is called cut-off frequency with time-varying, and the meaning of other parameters are similar to above explanation.

The new relationship derived in our method starts with the energy expressions of discrete-time signals proposed by Teager-Kaiser (1990) to get the computing expressions as equation (5) for seismic energy, and we used the Generalized S transform (GST) for the seismic instantaneous energy computing as equation (6). Then by calculating the amount of energy attenuation within the sampling wavelength, the expression of the relationship between the quality factor Q and the energy can be obtained as equation (7):

$$E=\frac{1}{2}\rho\omega^2A^2=2\pi^2\rho f^2A^2 \tag{5}$$

Where *E* is the seismic energy, *ρ* is the density of subsurface media, *A* is the seismic amplitude, and *ω* is the seismic angle frequency.

$$E(\tau,\ \omega)=\left[GST_N(\tau,\omega)\right]^2-\left[GST_N(\tau+\Delta\tau,\omega)\right]\cdot\left[GST_N(\tau-\Delta\tau,\omega)\right] \tag{6}$$

Where GST is the amplitude spectrum in time-frequency domain after Generalized S transform. So as we know, the seismic instantaneous energy is the maximum of the energy in the frequency domain. And the formation quality factor Q can be computed by following equation with calculating the amount of the energy attenuation rate.

$$Q(\tau)=\frac{2\pi E(\tau)}{E(\tau)-E(\tau+\Delta\tau)} \tag{7}$$

Where $E(\tau)$, $E(\tau+\Delta\tau)$ are the instantaneous energy of time at τ, and $\tau+\Delta\tau$ respectively.

Using equations (1), (2) and (3) with some deriving, we can get a new gain limits c(τ) of the amplitude compensation function and a new stabilization factor σ(τ) in our proposed inverse Q filtering as follows:

$$c(\tau)=\Phi\left(\tau,\omega_m(\tau)\right)=\frac{1}{2}\varphi\left(\tau,\omega_m(\tau)\right) \quad (8)$$

$$\sigma(\tau)^2=\frac{1}{4}\frac{f_m(\tau)\rho(\tau)\left(1-\frac{2\pi}{Q(\tau)}\right)}{f_m(\tau+\Delta\tau)\rho(\tau+\Delta\tau)-f_m(\tau)\,f_m(\tau+\Delta\tau)\sqrt{\rho(\tau)\rho(\tau+\Delta\tau)\left(1-\frac{2\pi}{Q(\tau)}\right)}} \quad (9)$$

Where the meaning of various symbols in equations (8)-(9) is same as previous explanation.
We can see σ is time-varying with the *Q(τ)* expressed by a smoothing continuous function. Finally, we use similar theory and method from Wang (2002) with the new σ to complete the inverse Q filtering. Basically, the gain of the compensation function in proposed time-varying method will increase when the attenuation and dispersion of seismic wave are strong with the subsurface media, such as in the high frequency band and in the deep layer, and vice versa. So the effects of the compensation both in amplitude and phase will be stable, and high resolution will be obtained by our new method.
Figure 1 shows the comparing results of the gain limits of the compensation functions from above mentioned three methods, we can see that our proposed method has the time-varying gain limits with smoothing continuous function.

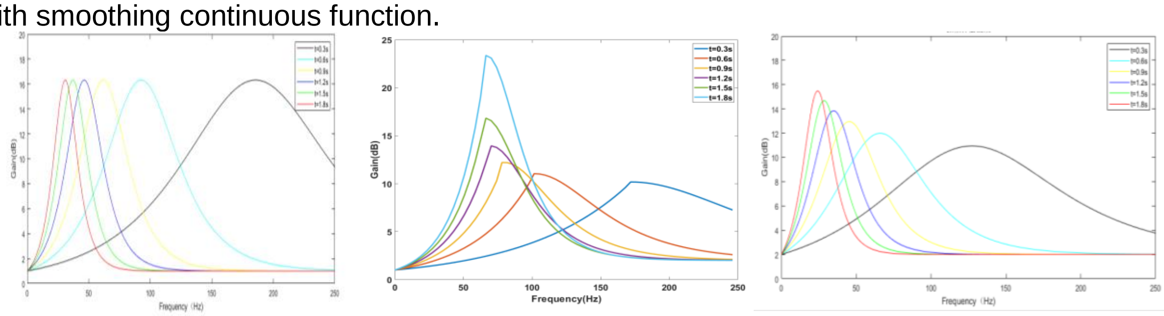

Figure 1 *Comparing results of different methods for gain limits of the compensation functions: left is Wang's method, the middle is Zhang's method and the right is our proposed method*

Synthetic Example

The following synthetic examples show the results of our method applied to one for post-stack model and another one for pre-stack model. Figure 2 shows the comparing results of a simple model by using different methods: (a) is synthetic records with different Q in the different layers; (b)-(d) are the results of Wang, Zhang and our methods. We can see that the results from our method is the best. Although the results of Zhang's method is similar to the results of proposed method, but some minor distortion in the deep layer can still be seen. Figure 3 shows the results for a pre-stack model, and we can also see that our method can give very good results compared with other methods.

Field Data Example

We would like to show one of the case studies in Bohai Bay basin, eastern China. In the study, we are facing the requirement to increase the resolution of seismic data by amplitude preserved processing for buried-hill reservoirs characterization in deeper (4500~5200 m) basement rocks.

Figure 4 showed the results of our method applied to the field data in the study area for target T8 horizon showed by black line. Figure 4(a) is one of the original section and (b) is the same section after using our inverse Q filtering. It is clear that the resolution of the seismic section, especially in the red square area, is highly improved after filtering and the data is more suitable for seismic reservoir characterization by using seismic inversion or attributes analysis. Figure 4(c)-(d) are the horizon slices of target T8 with RMS amplitude attributes. It is clear that the details of some RMS amplitude anomalies are more characterized in the (d) after inverse Q filtering compared with (c), e.g. in red circle area. Figure 5 shows the inversion results of another section for upper reservoirs of T8 before inverse Q filtering (a), and after inverse Q filtering (b). We can see that the resolution of the seismic data after filtering is highly improved, and the inverted impedance results after inverse Q filtering showed very good details of the reservoirs which is also corresponding to the well logging data. So the results showed the proposed inverse Q filtering methods is very useful to the reservoirs characterization in the study area.

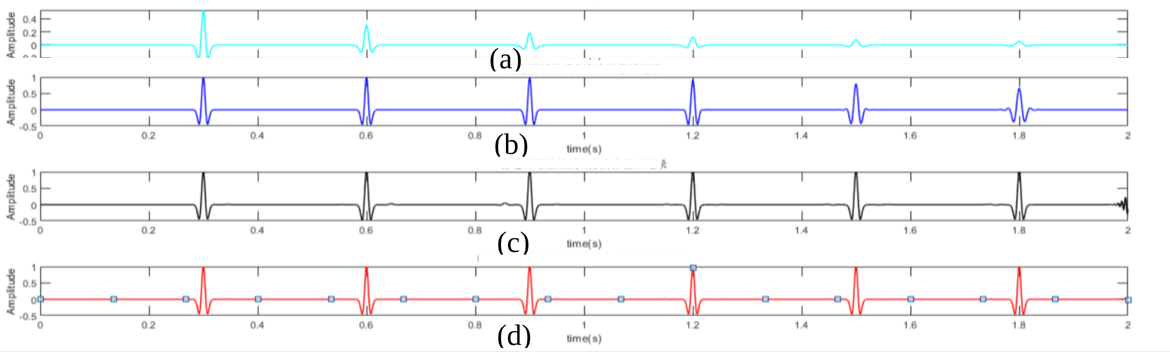

Figure 2 *Comparing results of different methods for inverse Q filtering of a simple model: (a) is synthetic records with different Q value, (b) is the results from Wang's method, (c) is the results from Zhang's method, and (d) is the results from our proposed method.*

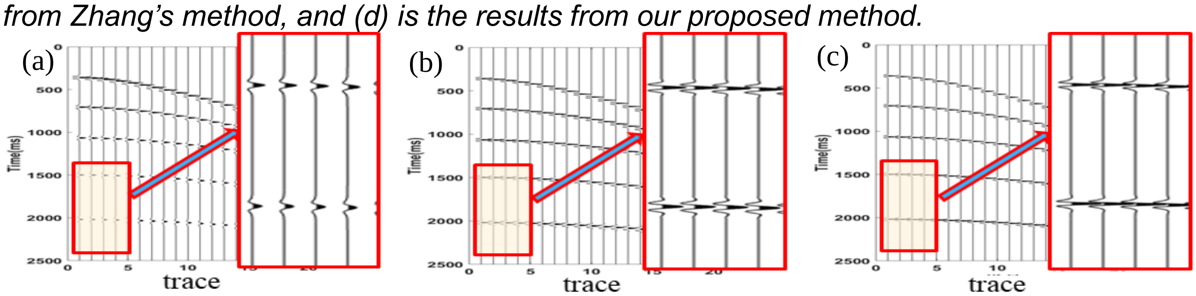

Figure 3 *Comparing results of different methods for pre-stack data: (a) is synthetic gather with attenuation by different Q value, and (b)-(c) is the results from Wang's method and proposed method.*

Conclusions

We have presented our new inverse Q filtering method with a time-varying gain limits of amplitude compensation expressed by a smoothing continuous function, which can properly handle and mitigate attenuation and dispersion of the amplitude and the change of the phases in the seismic reflection data with the change of absorption of different subsurface layers. We have presented some examples to prove 1) the validation of our method proposed with significant improvement

of increasing resolution and preserving the amplitude of seismic data; 2) the useful tool and good results in characterizing the deeper and complex basement reservoirs in the study area.
We would also like to mention that the inverse Q filtering method proposed in this paper depends very much on the formation quality factor Q value, and as we know, the accurate Q identification is a focusing area of current related research, which is also one of our main research projects currently and in future.

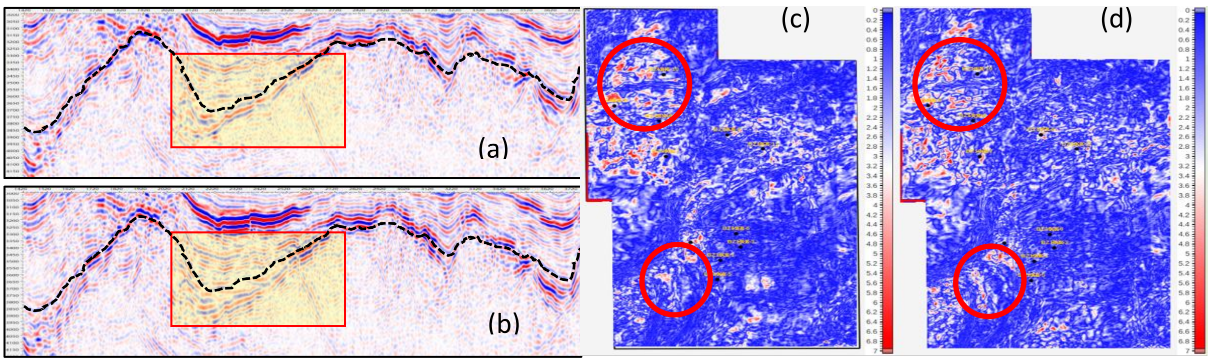

Figure 4 *The original seismic section (a), the section by using proposed method, (c)-(d) are horizon slice of RMS attributes before and after using the proposed method for target reservoir T8*

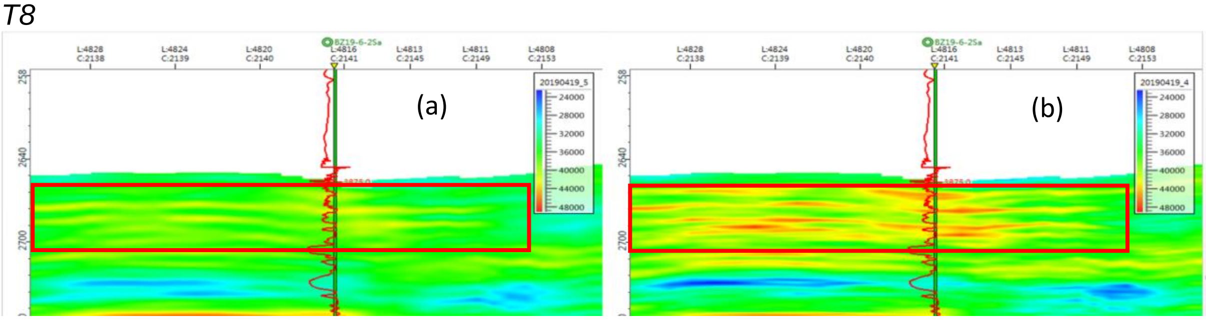

Figure 5 *The comparing results of impedance inversion before (a) and (b) after using proposed inverse Q filtering for the upper reservoirs of T8.*

Acknowledgements

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