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Research Status and Progress of Multiples Suppression Based on Radon Transform

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Abstract: The existence of multiple waves in seismic data has a substantial impact on earthquake imaging, inversion, and interpretation results. As a result, multiples are often suppressed as noise prior to seismic data preattack processing. Currently, there are two primary methods for suppressing multiple reflections in seismic data. One is a filtering technique based on geometric differences in the seismic waves, while the other is based on wave equation methods. The Radon transform, which suppresses multiple reflections, belongs to the class of geometric seismic diffraction filtering techniques. In the process of seismic data processing, it effectively separates multiple reflections from seismic data by utilizing the characteristic differences between primary and multiple reflections, thereby achieving noise attenuation and improving the signal-to-noise ratio of the data. This article primarily investigates the current state of methods for suppressing multiple reflections based on the Radon transform, both domestically and internationally. By introducing various forms and fundamental principles of the Radon transform, this study analyzes and compares the adaptability and pros and cons of each type of Radon transform. The high-precision Radon transform can effectively address the sawtooth phenomenon and energy dispersion issues that arise in the least-squares Radon transform. It also highlights the challenges associated with suppressing multiple reflections in the Radon transform and provides a glimpse into future developments.

Keywords: Radon transform; Multiple wave suppression; Research progress; High precision Radon transform.

1. Introduction

The Radon transform is a mathematical transformation method first proposed by the Austrian mathematician Radon. Its fundamental concept is to extract specific information from a signal by performing integral operations along specific paths. The Radon transform can be categorized into various types based on the difference in the integration path, such as linear Radon transform, hyperbolic Radon transform, parabolic Radon transform, polynomial Radon transform, elliptical Radon transform, among others. In the 1970s, the Radon transform was first introduced to geophysical exploration processing by Claerbout and Chapman. Since then, it has been widely applied in seismic data digital processing, with successful applications in seismic data denoising, decomposition of planar waves, multiple wave suppression, stacked velocity analysis, inversion, seismic interpolation and extrapolation.

The Radon transform has garnered significant attention in the industry for its operational flexibility and convenient application in suppressing multiple waves. Taner[1] initially proposed the utilization of linear Radon transformation for attenuating multiples. Hampson[2] proposed the parabolic Radon transform as a means of attenuating multiple reflections, in order to enhance the performance of the linear Radon transform. The parabolic Radon transform utilizes operator invariance to enhance computational efficiency and save time costs. However, it suffers from insufficient energy concentration, resulting in severe "tail" phenomena that adversely affect the suppression of multiple waves. Floster[3] improved the parabolic Radon transform and proposed the hyperbolic Radon transform to further suppress multiple waves. Wood[4] et al. proposed a high-resolution Radon transform based on the hybrid domain after research, which further improved the sparsity and resolution of the solutions in the Radon domain by taking advantage of the features of high resolution in the time domain and decoupling in the frequency domain. However, this method is expensive to calculate. Subsequently, Sacchi[5] proposed a high-resolution Radon transform, which effectively solved the "scissor-like" energy divergence problem, thus improving the accuracy of multiple wave suppression. However, increasing the number of iterations also leads to lower computing efficiency. Abbad et al[6]. proposed a fast algorithm for solving the problem in frequency domain based on singular value decomposition technology. By introducing variable λ, the relationship between conversion operator and frequency can be eliminated, namely, λ-f domain Radon transformation, which greatly improves the computational efficiency.

Chinese scholars have also carried out in-depth research on Radon transform to suppress multiple waves. Niu Binhua et al[7]. proposed a polynomial Radon transform by combining the advantages of parabolic Radon transform and linear Radon transform. The application of polynomial Radon transform has a better effect on the suppression of coherent linear noise. Liu Xiwu et al[8]. presented the implementation method of sparse constraint conjugate gradient method to solve the high-resolution Radon transform. Numerical examples show that the algorithm has high computational efficiency and accuracy, and can be better applied to multiple wave suppression. Wang Weihong et al[9]. proposed a weighted parabolic Radon transform in the processing of prestack seismic data, and successfully completed the reconstruction of missing trace of seismic data and the regularization processing of irregular sampling by using the introduced variable weighting coefficient. Aiming at the computational efficiency and resolution of the high-resolution Radon transform in different domains, Xiong Deng et al[10]. proposed the hybrid domain high-resolution parabolic Radon transform, introduced the time-varying sparse weight into the frequency domain parabolic Radon transform, and successfully applied it to the processing of prestack data

attenuation multiple waves. Based on Radon transform in λ-f domain, Li Zhina et al[11][12]. improved and optimized the methods of wave field separation and multiple suppression. Based on two-dimensional λ-f domain Radon transform, Shi Ying[13], Wang Weihong et al[14]. optimized and improved the seismic track reconstruction, wave field separation and multiple wave suppression methods. By adding sparse constraints to the conventional hyperbolic Radon transform, Fan Jingwen[15] proposed a high resolution hyperbolic Radon transform based on sparse inversion algorithm, which can effectively improve the local focusing effect of the velocity spectrum in Radon domain and has a good suppressing effect on multiple waves. Wang Liangliang et al[16]. implemented a 3D fast high-order Radon transform algorithm to eliminate the frequency dependence of 3D high-order parabolic Radon transform operator. By using CPU-GPU heterogeneous parallel algorithm, Zhang Quan et al[17]. obtained an acceleration ratio of about 30 times, which greatly improved the computing efficiency of Radon transform. Jing Hongliang et al[18]. proposed a λ-f domain 3D parabolic Radon transform to compress multiple waves based on two-dimensional parabolic Radon transform and after drawing on Abbad et al. 's method. By redefining the construction mode of the transform operator, the computational load was reduced and the computational efficiency was improved.

The following details several types of Radon transform and their advantages and disadvantages.

2. Several forms of Radon transformation

2.1. Linear Radon transforms

Linear Radon transform is the earliest application in geophysics. It is mainly used to suppress linear noise of image surface wave class and reconstruct seismic trace interpolation. Its integral path is $t = \tau + px$, and the given path is linear, also called linear Radon transformation is τ-p transformation. The linear Radon transform has the property of time invariance in the time domain. According to this property, it can be transformed into the frequency domain for related calculation, which can not only improve the calculation efficiency, but also not reduce the calculation accuracy.

2.2. Hyperbolic Radon transforms

The linear Radon transform is mainly applicable to the linear noise of surface waves, and the in-phase axis of the actual seismic data reflected on the CMP track set and gun set is curved hyperbola. In this case, the hyperbolic integral route $t = (\tau^2 + px^2)^{1/2}$ is selected, so the hyperbolic Radon transform will be more suitable for the actual seismic data and will be applied more widely.

Since the integral route of hyperbolic Radon transform is $t = [\tau^2 + (x/v)^2]^{1/2}$, its characteristic in time domain is time varying, which determines that hyperbolic Radon transform cannot be converted to the corresponding frequency domain for calculation and processing, and its calculation efficiency is low in time domain, thus affecting the processing process of seismic data. In seismic data processing, hyperbolic Radon transform is well used to reconstruct seismic trace loss and suppress multiple waves.

2.3. Parabolic Radon transformation

Since hyperbolic Radon transform is not coupled in frequency domain, its calculation efficiency is low and the calculation time is too long. The parabolic Radon transform is time-invariant, and the data in the frequency domain can be obtained after Fourier transform. In the frequency domain, the parabolic Radon transform is decoupled, so the computational efficiency is greatly improved. In the CMP track set and gun set, the in-phase axis of the actual seismic data reflection wave is a curved hyperbola, and the prerequisite of parabolic Radon transformation is that the in-phase axis of the track set is a parabola. Parabolic Radon transform can be applied to multiple wave suppression, seismic track data reconstruction and velocity analysis.

3. Least square Radon transform and high precision Radon transform

The least square parabolic Radon transform ensures the stability of inversion by introducing damping regularization operator and has the characteristics of high computational efficiency. However, the point aggregation of energy in Radon domain is not good, and divergence scissor-like phenomenon occurs, resulting in partial effective wave and multiple wave energy intermixed with each other. The design of the excision area is too large or too small will affect the effect of compression. Too large resection will damage the effective signal energy, too small resection will residual multiple waves, and some weak noise will be generated in the t-x domain after inverse transformation, which will reduce the resolution of the stack profile.

In order to solve the resolution problem of the least square Radon transform, Sacchi et al. combined with Bayes principle and constructed the relevant prior information of the model to constrain the regularization operator, thus introducing the high-resolution Radon transform. Using the minimized new objective function, the relevant iterative formula of sparse constraint inversion function can be deduced. The expression of least square objective function is as follows:

$$\mathbf{J} = \|(d - \mathbf{L}r)\|^2 + \mu\|r\|^2 \quad (1)$$

On the type, $\|(d - \mathbf{L}r)\|^2$on behalf of the inversion error, $\mu\|r\|^2$ on behalf of the regularization item.

Using Cauchy probability density distribution function, the updated objective function can be obtained:

$$\mathrm{J} = \|(d - Lr)\|^2 + \eta\sigma_r^2 \sum_{i-1}^{N_p} \ln(1 + \frac{r_i^2}{\sigma_r^2}) \quad (2)$$

Among them, σr represents the weighted value of the prior parameters, η represents the prior information parameter of the smoothness and sparsity of the data in the conversion domain. The value of σr is generally small and related to the suppression of the reflection axis. Its main function is to ensure that the function must be continuously derivable, and the value range is between 0 and 1. Then the expression of r correlation solution is:

$$r = \left[\mathbf{L}^H\mathbf{L} + \eta\boldsymbol{diag}(\frac{\sigma_r^2}{\sigma_r^2 + r_i^2})\right]^{-1}\mathbf{L}^H d \quad (3)$$

In the above equation, diag is a diagonal matrix. Since it is a nonlinear objective function, r -value is the value estimated by several iterations updated by the least square algorithm. Since formula (3) is a nonlinear function, the definition of the model sparsity regularization term is defined. So the bidirectional conjugate gradient method is used to solve the problem.

Since covariance matrix plays a key role in processing waste track and abnormal amplitude of data, the covariance matrix is introduced into Formula (2), and the corresponding expression of its model domain solution is as follows:

$$r = (\mathbf{L}^H \mathbf{C}_n^{-1} \mathbf{L} + \mathbf{C}_r^{-1})^{-1} \mathbf{L}^H \mathbf{C}_n^{-1} d \quad (4)$$

In the above equation, Cn represents the covariance matrix to be denoised, and Cr represents the model covariance matrix.

$$[\mathbf{C}_r]_{i,j} = 2\sigma_r |r_i| \quad (5)$$

$$[\mathbf{C}_r]_{i,j} = \sigma_r^2 + r_i^2 \quad (6)$$

The above two formulas are commonly used to estimate sparse models. Given a small constant weight coefficient as the threshold value ε, after corresponding changes, the corresponding expression of [Cr]i, j is:

$$[\mathbf{C}_r]_{i,j} = \begin{cases} 2\sigma_r |f_i| f_i > \varepsilon \\ 2\sigma_r |\varepsilon| f_i \le \varepsilon \end{cases} \quad (7)$$

In the above equation, σr represents the preset dispersion noise. The weighting factor in the least square Radon transform is a fixed value, which can be processed in the corresponding domain. In order to eliminate the influence of false frequency, the value of weighting factor is generally large. But when the value is small, you get false energy. In order to obtain high-precision Radon transform, the weighting factor needs to be modified accordingly. The following is the expression of high-precision Radon transform:

$$(\mathbf{L}^H \mathbf{L} + \mathbf{W}^H \mathbf{W}) r = \mathbf{L}^H d \quad (8)$$

In the above equation, W is represented as a diagonal matrix, and its expression is as follows:

$$\mathbf{W}_{i,j} = \boldsymbol{\varpi}_i \xi_{i,j} \quad i, j = 1,2, \dots, r \quad (9)$$

In the above equation, since i and j are variables, the focusing matrix W also changes accordingly and is no longer fixed and updated with each iteration. In Equation (8), its weighting matrix is also inconsistent with Teoplitz matrix, and its expression is:

$$\mathbf{L}^H \mathbf{L} + \mathbf{W}^H \mathbf{W} = \sum_k^N \exp(-2\pi f (p_i - p_j) x_k^2) + \varpi_i^2 \xi_{i,j} \quad i, j = 1,2, \dots, r \quad (10)$$

The weighted matrix is determined by the relevant seismic information in the transform domain, so as to improve the resolution of seismic data, which plays a crucial role in the high-precision Radon transform in the frequency domain. After the initial model is known, the desired result can be obtained through multiple iterations of updates.

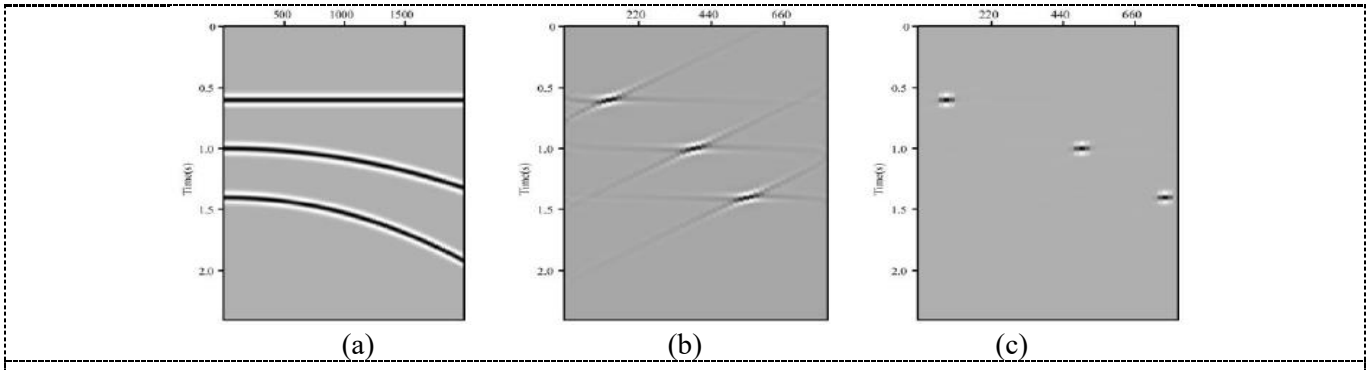


Figure 1. The results were compared before and after using different Radon transform methods
(a) This is the raw seismic data (b) This is the result of the least squares Radon transform (c) This is the result of the high-precision Radon transform

FIG. 1 shows the results of Radon transform applied by different methods. It can be seen that the results in FIG. (b) after the least squares Radon transform method are obviously scissor-like and the energy diverge and does not focus. However, after the high-precision Radon transform method in Figure (c) is selected, the energy clusters are more focused in the corresponding domain, indicating that the illusion caused by the aperture effect is well suppressed.

4. Conclusion

Radon transformation is an inversion process. Seismic data is converted to Radon domain to separate different components, retain effective components, eliminate unnecessary components, and finally reverse back to the original domain to retain only effective signals to achieve the effect of multiple wave suppression. Through continuous research and development, Radon transform is widely used in the actual seismic data. It can be well applied in the actual seismic data processing and has a good effect on the suppression of multiple waves. However, it needs to be pointed out that Radon transform method still has the disadvantage of Radon class method when suppressing multiple waves, that is, when the velocity difference between the secondary wave and the multiple wave is small, it cannot get the ideal suppressing effect of multiple waves at near offset, which needs to be further developed and perfected.

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