Improving Resolution of Seismic Sections Based on Method of Information Fusion with Well-log Data

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Abstract - A method of extrapolating the high frequency information from the well-log into the cross-well seismic sections was proposed in this paper. Employing the Sort-Time Fourier Transform (STFT) and an average coherence coefficient that was defined in this paper, the local correlation between two adjacent seismic traces was calculated in the frequency domain. Then depending on the proposed transfer function we transfer the high frequency information of a well-log into its nearby traces, and then from one high resolution trace into its adjacent traces one by one to get the desired high resolution seismic section.

Keywords: information fusion, short-time Fourier transform, high-resolution seismic signal processing

1. Introduction

In today's petroleum industry, one important source of information for oil/gas exploration and production is seismic data, and improving the vertical resolution of seismic data is an important task in seismic signal processing. With the development of modern signal processing technology, the resolution of seismic sections has already been improved greatly. Yet the requirement from the industry is far from fully satisfied. As the information in the seismic records is limited, it is very difficult to further enhance their resolution depending solely on signal processing techniques. Fusing other information about the strata in seismic data processing is an effective way to solve this problem.

Usually in oil exploration bore-holes or wells will be drilled at locations of particular interests in a survey. In this case logging sondes will be placed in the bore-hole and pulled upwards, measuring rock velocity and density of the subsurface rocks as well as other geophysical parameters. Since a reflection coefficient is the difference in acoustic impedance of two layers, over their sum, and acoustic impedance is given by velocity times density, it is thus possible to construct a series that is close to the true reflective coefficient sequence from well logs. It has the highest possible vertical resolution on the spot of well. In other words, it has the highest frequency extent. How to use its high frequency information to enhance the resolution of seismic sections across the well is a newly problem in the study of seismic signal processing.

In general, it is reasonable in geophysics to assume that there exists good local correlation between most adjacent seismic traces. And, through some processing there can also exist good local correlation between the well-log and its nearby traces. This observation is the basis of improving resolution of seismic sections using information of well-logs. Based on this observation Luo and Li proposed an initial idea of extrapolating high frequency information from well-logs into seismic section using the short-time Fourier transform[1]. But there exist many aspects that need to be further improved so that the method can be practicable.

In this paper, we proposed a new method for enhancing the resolution of cross-well seismic sections by fusing high-resolution well-log information into the processing. We first extract the high frequency components of the well-logs and extrapolate them to the near-well seismic trace, to get a new higher resolution trace. Then the high frequency information of this new trace

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is transferred to its adjacent traces. This procedure is executed trace by trace so that a whole new seismic section of higher resolution can be finally derived. The key of this method is to extrapolate the high frequency information from a well-log to a near-well trace, and from one trace to its adjacent trace. In order to estimate the local correlation between two adjacent traces exactly, we calculate the short-time Fourier transform (STFT) of a high-resolution trace and its adjacent low-resolution trace respectively. Then the high frequency component of STFT amplitude of the adjacent trace is extended or is modified by some transfer function, which is designed based on the local correlation of the two traces in frequency domain. From the modified STFT amplitude of this adjacent trace, a new seismic trace whose resolution has been enhanced can be constructed with inverse STFT. By this processing, the high frequency information contained in well-log data is effectively fused into the seismic data, and at the same time, the original information of seismic data is well preserved at the same time.

Experimental results on both synthetic seismic data and field seismic data proved the effectiveness of our new method.

2. The Model

In seismic signal processing, a well-known discrete convolution model is

\[ y_t^k = r_t^k \ast w_t + n_t^k = \sum_{l} r_{t-l} w_t + n_t^k, \quad k=1,2,\ldots, \]  

where \( y_t \) is the seismic signal, \( r_t \) is the primary reflective coefficient sequence of strata, \( w_t \) is the seismic wavelet, and \( n_t \) is additive noise. The subscript \( t \) is two-way reflection time, and superscript \( k \) is the number of seismic trace. In general situation, the series \( \{y_t\} \) may be analyzed as stationary, and furthermore, from detailed investigations in [2], may be taken as having a zero mean and having a square summable auto-covariance sequence so that their spectra exist in the usual mean square sense.

In equation (1) we assumed that the seismic wavelet of each trace is same in one section. This assumption is appropriate for actual post-stack sections[3]. The problem of enhancing the resolution of seismic section is to compress the width of seismic wavelet, or to extend the width of frequency band of sequence \( \{y_t\} \). For convenience, we ignore the item of noise in (1) the following discussion.

If we denote the series \( \{r_t^0\} \) as the reflective coefficient that is taken from the data of well-logs, we can use a wavelet \( \{w_t^0\} \), whose frequency band can be intentionally selected, to make a synthetic seismic trace. We denote it as \( \{v_t\} : \)

\[ v_t = r_t^0 \ast w_t^0 = \sum_n r_{t-n} w_t^0. \]  

If we select a higher frequency wavelet in above equation, we can get a higher resolution synthetic seismic trace, contrarily, we can also get a lower resolution synthetic seismic trace. We denote the higher frequency wavelet and lower frequency wavelet of synthetic seismic data as \( \{w_t^{0H}\} \) and \( \{w_t^{0L}\} \) respectively, and the synthetic seismic trace corresponding with them is denoted as \( v_t^H \) and \( v_t^L \).

3. Estimation of Local Correlation between Adjacent Traces

Let the near trace of \( \{v_t\} \) be \( \{y_t^1\} \). In spite that \( \{y_t^1\} \) and \( \{v_t\} \) are coming from different physical methods, they all represent information of strata at the same local position. Because the change of strata is relatively slow in the horizontal direction, \( \{y_t^1\} \) and \( \{v_t\} \) can be considered to be highly correlated. Actually, any two adjacent traces are highly correlated in most local ranges of traces.

Let \( s_{0v}(\tau) \) be cross-correlation function between well synthetic trace \( \{v_t\} \) and its near trace \( \{y_t^1\} \). It is defined as

\[ R_{0v}^{0}(\tau) = E[v_t y_{t+\tau}^1] = \frac{1}{N} \sum_{l=0}^{N-\tau-1} v_l y_{l+\tau}^1, \]  

where \( N \) is the length of series. For computing a local correlation between \( \{v_t\} \) and \( \{y_t^1\} \), we
modify above equation with a window function \{p_t\}. Then,

\[ R^0_{y}(l, \tau) = \frac{1}{N_p} \sum_{k=0}^{N_p-\tau} v_k y^0_{l,t+k}, \quad (4) \]

where

\[ v_{l,t} = v_t p_{l-t}, \]
\[ y^0_{l,t} = y^0_t p_{l-t}, \]

and \( l \) is time, \( N_p \) is the width of the window function, which has a short-time duration.

Imitating equation (2), the auto-correlation of \( \{v_t\} \) and \( \{y^1_t\} \) are

\[ R^0_v(l, \tau) = \frac{1}{N_p} \sum_{k=0}^{N_p-\tau} v_k v_{l,t+k}, \quad (5) \]
\[ R^0_y(l, \tau) = \frac{1}{N_p} \sum_{k=0}^{N_p-\tau} y^1_k y^1_{l,t+k}. \quad (6) \]

Their Fourier transforms \( R^0_v(l, \tau), R^0_y(l, \tau) \) and \( R^0_y(l, \tau) \) give the cross-spectral density function between \( \{v_t\} \) and \( \{y^1_t\} \), and auto-spectral density functions of \( \{v_t\}, \{y^1_t\} \), which are denoted as \( S^0_v(l, f), S^0_y(l, f), S^0_y(l, f) \) respectively. From above spectral density functions, the coherence function \( \gamma^2_{vy}(l, f) \), which measures the linear correlation between the components of \( \{v_t\} \) and \( \{y^1_t\} \) at frequency \( f \) in a local range, can be defined as

\[ \gamma^2_{vy}(l, f) = \frac{|S^0_v(l, f)|^2}{S^0_v(l, f) S^0_y(l, f)}. \quad (7) \]

The coherence function can be seen being normalized, and it is sort of a correlation coefficient in the frequency domain[4]. If \( v_{l,t}=y^1_{l,t} \) (maximum correlation between \( \{v_{l,t}\} \) and \( \{y^1_{l,t}\} \)), then

\[ \gamma^2_{vy}(l, f) = \frac{|S^0_v(l, f)|^2}{S^0_v(l, f) S^0_y(l, f)} = 1. \quad (8) \]

On the other extreme, if \( v_t \) and \( y^1_t \) are uncorrelated, then \( S^0_v(l, f) = 0 \) and \( \gamma^2_{vy}(l, f) = 0 \).

We define an average coherence coefficient \( \overline{\gamma}^2_{vy}(l) \) as

\[ \overline{\gamma}^2_{vy}(l) = \frac{1}{N_f} \sum_{f=0}^{N_f-1} \gamma^2_{vy}(l, f), \quad (9) \]

where \( N_f \) is number of samples in frequency domain. The function \( \overline{\gamma}^2_{vy}(l) \) measure the average value of local correlation between the components of \( \{v_t\} \) and \( \{y^1_t\} \) in frequency domain. It is only the function of time \( l \). Alike the coherence function \( \gamma^2_{vy}(l, f) \), if \( v_{l,t}=y_{l,t} \), then \( \overline{\gamma}^2_{vy}(l) = 1 \), and if \( \{v_{l,t}\} \) and \( \{y^1_{l,t}\} \) are un-correlated then \( \overline{\gamma}^2_{vy}(l) = 0 \).

4. Transfer Function and the Information Transfer

The basic method of enhancing the resolution of seismic section in this paper is to realize the extrapolation of high frequency information from well-log synthetic trace to its nearby traces, and then from one higher resolution seismic trace to its adjacent lower resolution seismic trace one by one. This means that the processing of extrapolation should be in the frequency domain. On the other hand, since strata vary along the horizontal direction, the values of correlation in the different local segments of any two adjacent traces are different. From this property the extrapolation should be of the time-varying. STFT is a useful tool for analyzing and processing the problem of time-frequency. We employed it in our method.

Denote the STFT of series \( \{v_t\} \) is \( SF_v(l, f) \), then

\[ SF_v(l, f) = \sum_{k=-\infty}^{\infty} v(k) p(l-k) e^{-j2\pi kf}. \quad (10) \]

The above equation can be rewritten in form of the amplitude spectrum \( |SF_v(l, f)| \) and corresponding phase spectra \( \Phi_v(l, f) \),

\[ SF_v(l, f) = |\sum_{k=-\infty}^{\infty} v(k) p(l-k) e^{-j2\pi kf}| e^{j\Phi_v(l, f)}. \quad (11) \]

Replacing \( v \) with \( y \) in equation (11) we can get \( |SF_y(l, f)| \) and \( \Phi_y(l, f) \).

The transfer function is used to transfer the
5. The Procedure of Fusing Well-log Information into Seismic Traces

In section 3, we showed the correlation measurement of two adjacent traces in frequency domain. In section 4, we gave a definition of transfer function and put forward the method of transferring the high frequency information from a synthetic trace to its nearby traces. Based on those, the whole procedure of fusing well-log information into seismic trace is presented.

First, using the reflective coefficient sequence, which is from a well-log data, and two known wavelets, one frequency is higher and another is lower, we generate two synthetic seismic traces with the convolution model (2), i.e. \( \{ v_t^{H} \} \) and \( \{ v_t^{L} \} \), which have higher and lower resolution respectively. It is worth noting that the lower resolution synthetic seismic trace \( \{ v_t^{L} \} \) is only used to match its near trace \( \{ y_t^{L} \} \), so its wavelet should be as same as \( \{ y_t^{L} \} \). In the best way, this wavelet should be extracted from \( \{ y_t^{L} \} \).

Secondly, to calculate the local cross-correlation \( R_y(l,\tau) \) between the lower frequency synthetic seismic trace \( \{ v_t^{L} \} \) and its nearby trace \( \{ y_t^{L} \} \) with the equation (4). Because the seismic section has the slope line, the local cross-correlation between two adjacent traces may be not in the same time point. Therefore, we should find the maximum of the cross-correlation between \( \{ v_t^{L} \} \) and \( \{ y_t^{L} \} \) in a small time range \([-M, M]\). In this situation, the equation (4) is modified as

\[
R_y^{M}(l,\tau) = \max_{m \in [-M, M]} \frac{1}{N_p} \sum_{k=0}^{N_p-1} v_t^{L} y_t^{L}_{M+m, \tau},
\]

where parameter \( M \) is selected according to the degree of slope of the line in seismic section. Beside the \( R_y^{M}(l,\tau) \), we should calculate the local auto-correlation function of \( \{ v_t^{L} \} \) and \( \{ y_t^{L}_{M+m, \tau} \} \), denote \( R_y(l,\tau) \) and \( R_y^{M}(l+m_0,\tau) \), with equation (5) and (6), where \( m_0 \in [-M, M] \) is the time point that make \( R_y^{M}(l,\tau) \) maximum in (15).

After getting \( R_y^{H}(l,\tau) \), \( R_y(l,\tau) \) and \( R_y^{M}(l+m_0,\tau) \), Fourier transform them to get power spectrums, \( S_y^{H}(l,f) \), \( S_y(l,f) \), \( S_y^{M}(l+m_0,f) \), then using equation (9) to calculate the average coherence coefficient \( \bar{\gamma}_y^2(l) \).

Finally, transfer frequency information from the synthetic seismic trace \( \{ v_t^{H} \} \) to its nearby trace \( \{ y_t^{L} \} \) so that a new higher resolution trace will be got. We denote it by \( \hat{y}_t^{L} \). For this purpose, we compute the STFT of \( \{ v_t^{H} \} \) and
{y_t^1}, get the amplitude spectrum |SF_y(l,f)| and \(|SF_y^0(l+m_0 f)|\), and the phase spectrum \(\Phi_y(l, f)\) from (10). Then, from equation (14) the amplitude spectrum of STFT of \(\{\hat{y}_t^1\}\), i.e. \(|SF_y(l,f)|\) is given. Using the following equation,
\[
\hat{y}_t^1(l) = \frac{1}{2\pi} \sum_{m} |SF_y(l,f)| e^{i(2\pi f l + \Phi_y(l,f))},
\]
where \(l, t = 0, 1, \ldots, N_y\), we can reconstruct the seismic trace \(\{\hat{y}_t^1\}\).

Replacing the \(\{v_t^0\}\) with \(\{\hat{y}_t^1\}\), and replacing \(\{y_t^1\}\) with \(\{y_t^2\}\), we repeat above procedure, the higher resolution trace \(\{\hat{y}_t^2\}\) can be given. Imitating this the information of well-log can be transfer into the whole seismic section.

6. Experiments

In order to check the performance of the method that was proposed above, we first transfer the information from a well-log into its nearby trace using the simulated signals. Fig.1(a) is a simulated sequence of reflective coefficient that was taken from well-log data. Fig.1(b) is a synthetic seismic trace which is the convolution of a higher frequency wavelet and the sequence of Fig.1(a). Fig.1(c) is the trace near the well which was generated with reflective coefficient sequence that is showed in Fig.1(f). Using the method presented above, we transferred the higher frequency information from Fig.1(b) into Fig.1(c), the result or output trace is showed in Fig.1(d). Comparing Fig.1(c) with Fig.1(d), the resolution of original trace has been enhanced evidently. Fig.1(e) is the real high resolution trace corresponding with Fig.1(c), which is generated from convolution between a high frequency wavelet and correspondent real reflective coefficient sequence Fig.1(f). Comparing Fig.1(d) and Fig.1(e), we can find that result of the procedure of information transfer is quite similar with its real situation.

Another result of the experiment with a real-world seismic data is shown in Fig.2. Fig.2(a) is an original seismic section which are from certain area in China. Fig.2(b) is the processed seismic section using above method. In fig2(b) we inserted two high frequency synthetic seismic traces that were repeated to form several same traces, which are the source of the high resolution of seismic section. From fig.2(b) we can see that the resolution is much higher than the original seismic section, while the basic structures are well reserved.

7. Conclusion

In this paper we defined the local average coherence coefficient, and proposed a new transfer function. Based on them a new method of fusing well-log information to enhance the resolution of seismic section was given. Experiment examples showed its good effect.
References

Figure 2. Experiment with real-world seismic section (part).
(a) original seismic section;  (b) processed seismic section with synthetic traces at well locations.