RANDOM NOISE SUPPRESSION OF MRS OSCILLATING SIGNALS USING SEGMENT TIME-FREQUENCY PEAK FILTERING

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Abstract

Compared with the other geophysical approaches, magnetic resonance sounding (MRS) technique is direct and nondestructive in subsurface water exploration and it has been developed quickly in recent years. The magnetic resonance sounding (MRS) oscillating signals are recorded with high sampling rate, so the comprehensive information in the signals provides more potential in signal processing and inversion interpretation. However, MRS measurement always suffers bad signal-to-noise ratio (SNR). For the random noise interference, due to its stochastic properties, it always distributes arbitrarily. Normally, random noise appears randomly in signal recordings and difficult to remove. As long as the average magnitude of random noise is larger than that of signal, the accuracy of parameter estimation will be reduced. The general objective of this study is to solve the problem of the oscillating MRS signals contaminated with random noise. We propose to use segment time-frequency peak filtering method, the MRS oscillating signal is divided into several segments, and each segment of the signal is transformed into the instantaneous frequency of analytic signal. Then a significant energy concentration is produced around the IF on the time-frequency plane of analytic signal, and the unbiased estimation of underlying MRS signal is achieved by taking the peak of Wigner-Ville distribution of analytic signal. The validity of theoretical considerations is demonstrated by numerical simulations, it shows that the desired MRS oscillating signal can be recovered in noise level down to a SNR of -5 dB.

Introduction

The method of magnetic resonance sounding (MRS) can detect the abundant degree of hydrogen nucleus in subsurface directly, which has the ability to determine the aquifer depth, thickness and water content(e.g. Yaramanci *et al.* 2002; Perttu *et al.* 2011). It has been widely applied in hydrogeological investigation(Legchenko *et al.* 2002). But the low signal-to-noise ratio is always the main reason to restrict the application of this method. Hence, it is significant to remove noise from MRS data samples.

The noises disturbing MRS signal mainly include random noise, spike noise and power-line harmonic noise, several effective noise-cancelling approaches are proposed mainly focused on de-spiking and harmonic noise cancellation (e.g. Legchenko & Valla 2003; Walsh 2008; Jiang *et al.* 2011; Dalgaard *et al.* 2012; Müller-Petke & Costabel 2014; Larsen 2016). But the methods about random noise attenuation are rarely reported in the current literature. At present, the widely-used method is stacking, that is averages multiple measurements. However, the effect of stacking is limited in a noisy environment, and stacking is time-consuming. Time-frequency analysis has being a novel method in signal processing, of which time-frequency peak filtering (TFPF) is an innovative alternative which developed by Arnold et al. (1994). The idea for signal enhancement by TFPF method is initially used in newborn electroencephalogram (e.g. Boashash & Mesbah 2004), then applied in seismic fields (e.g. Wu *et al.* 2016), and a series of research results have been achieved. The goal of this paper is to use the advantages and characteristics of TFPF for random noise attenuation to further enhancement of SNR in MRS signal.

However, measuring the MRS oscillating signal requires a high sampling rate, so the amount of the recorded data is large. In order to reduce the requirement for computer performance and increase the processing speed, we propose segment time-frequency peak filtering (STFPF) to process the MRS oscillating signal. The performance of the proposed method is discussed in numerical simulations. Besides, the effectiveness of the proposed method is further demonstrated by the retrieved model after inversion.

Method

Assume that the noisy MRS oscillating signal processed by STFPF method can be modeled as

$$x(m) = s(m) + n(m) \tag{1}$$

where m is the discrete time samples, $s(m)$ is the desired signal from hydrogen protons in subsurface and $n(m)$ is random noise which may have overlapping spectra. In order to effectively extract the desired signal, the MRS oscillating signal is first divided into several segments. Let the length of the MRS oscillating signal is M, the number of the segments is I and the length of each segment is W, thus each segment of the signal can be expressed as

$$x_i(m) = \begin{cases} x(m), (i-1)\mathrm{W}+1 \le m \le i\mathrm{W}, i = 1, 2, \ldots, \mathrm{I}, \\ 0, \text{others.} \end{cases} \tag{2}$$

When $\mathrm{I} \times \mathrm{W}$ is larger than M, the last segment of the signal is composed by the residual sampling points, that is $x_{\mathrm{I}}(m) = x(m), (\mathrm{I}-1)\mathrm{W}+1 \le m \le \mathrm{M}$.

Then, scaling is performed on each segment of the signal, which is followed by

$$x_{ic}(m) = (a-b)\frac{x_i(m) - \min[x_i(m)]}{\max[x_i(m)] - \min[x_i(m)]} + b \tag{3}$$

where $x_{ic}(m)$ is the signal after scale transformation. Parameters a and b satisfy the constraint $0.5 \ge a = \max[x_{ic}(m)]$ and $b = \min[x_{ic}(m)] \ge 0$. These are chosen to provide suitable frequency limits on the encoded signal.

Encode the noisy MRS signal as the instantaneous frequency of analytic signal as follows

$$z_{x_{ic}}(m) = e^{j2\pi\mu \sum_{\lambda=1}^{\mathrm{M}} x_{ic}(\lambda)} \tag{4}$$

where μ is a scaling parameter and $z_{x_{ic}}(m)$ is the analytic signal.

Calculate the time-frequency distribution of analytic signal using pseudo-Wigner-Ville distribution. Discrete pseudo-Wigner-Ville distribution of $z_{x_{ic}}(m)$ can be expressed as

$$W_{z_{x_{ic}}}(m,k) = 2\sum_{l=-(2L-1)}^{2L-1} w(l) z_{x_{ic}}(m+l) z_{x_{ic}}{}^{*}(m-l) e^{-j2\omega k} \tag{5}$$

where $w(l)$ is a window function. It is even symmetry whose length is 4L-1. When $|l| \geq 2L$, $w(l)=0$.

Then take the peak of $W_{z_{x_{ic}}}(m,k)$ to estimate the IF, which is given by

$$\hat{s}_{ic}(m)=\frac{\arg_f \max\left[W_{z_{x_{ic}}}(m,k)\right]}{u} \qquad (6)$$

The estimate of the desired signal is recovered by an inverse scaling operation, that is

$$\hat{s}_i(m)=\frac{(\hat{s}_{ic}(m)-b)(\max[x_i(m)]-\min[x_i(m)])}{a-b}+\min[x_i(m)] \qquad (7)$$

where $\hat{s}(m)$ denotes the filtered MRS signal, and $\hat{s}_c(m)$ is the scaled signal obtained using TFPF on $x_c(m)$.

Finally, sum up each filtered segment to obtain the complete filtered result as following

$$\hat{s}(m)=\sum_{i=1}^{\mathrm{I}}\hat{s}_i(m-(i-1)\mathrm{W}), m=(i-1)\mathrm{W}+1,\ldots,i\mathrm{W} \qquad (8)$$

To demonstrate the validity of the proposed method, a numerical experiment has been carried out. Fig.1a shows a simulated MRS oscillating signal with the initial amplitude $E_0=200\mathrm{nV}$, the transverse relaxation time T_2^*=150ms, phase shift φ_0 -1.05 rad is and the Larmor frequency f_{L} is 2128 Hz. The sampling frequency is 50 kHz. The MRS signal was corrupted by random noise with a mean value of 0 nV and a standard deviation of 100 nV, making the SNR is -5.17 dB. Then, STFPF method is implemented to eliminate the random noise and acquire the estimation of the signal parameters, the initial amplitude achieved is 254.98 nV and the transverse relaxation time is 998 ms. Transform the noisy signal into an analytic signal and calculate the distribution of the analytic signal using PWVD, which is shown in Fig.1b. The observation implied that a significant energy concentration was produced and the signal could be estimated by maximizing the PWVD of the analytic signal along the frequency axis.

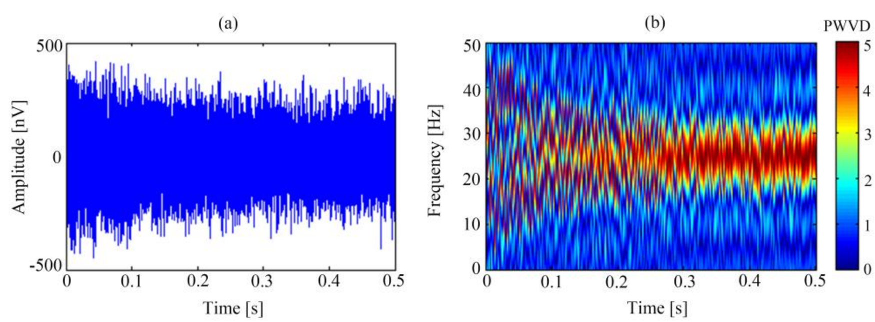

Figure 1. The noisy MRS oscillating signal and the time frequency distribution of its analytic signal. (a) Simulated MRS oscillating signal which embedded in random noise; (b) PWVD of the analytic signal.

The filtered signal in red is illustrated in Fig.2a. Here, the signal was divided into 100 segments and each segment consists 250 sampling points. Fig.2b zoom in the signal at 2 ms~5 ms and Fig.2c zoom in the signal at 112.6 ms~ 115.2 ms. After suppressing the random noise, the SNR of the signal is 18.02 dB, the initial amplitude is 206.06 nV and the transverse relaxation time is 164 ms. The SNR is increased 23.19 dB. The fitting error of initial amplitude is 27.49 % before filtering and 3.03% after filtering, the transverse relaxation time is 565.3 % before filtering and 9.3% after filtering.

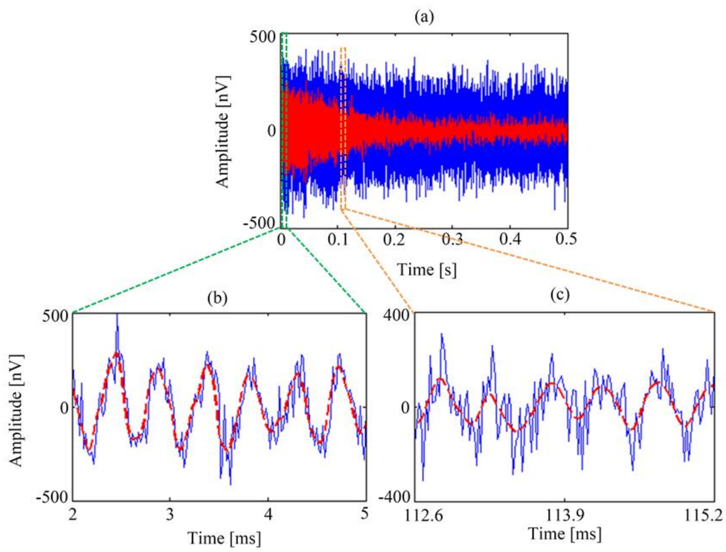

Figure 2. The filtered signal in time domain
(a) A complete signal; (b) signal at 2 ms~5 ms; (c) signal at 112.6 ms~115.2 ms.

The random noise was suppressed effectively and in order to compare the detail feature of the signal before and after filtering, the time-frequency distribution of the signal is shown in Fig.3.

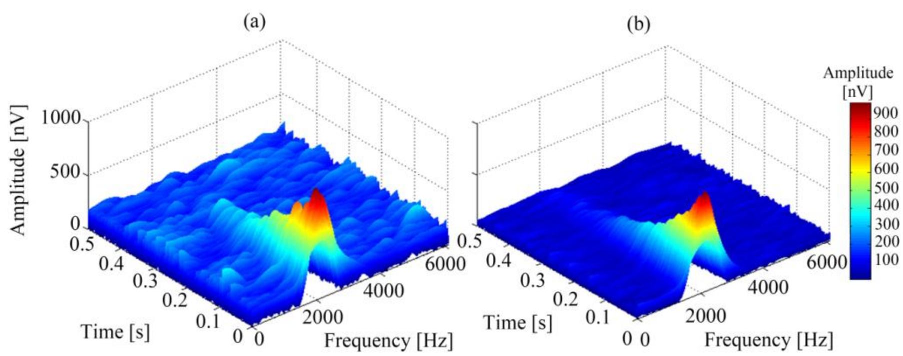

Figure 3. Time–frequency distribution of the signal before and after filtering
(a) before filtering; (b) after filtering.

From Fig.3, we can observe that the frequency of the signal is 2128 Hz, it is a decaying signal varying with time. The energy of the random noise is distributed on the whole time-frequency plane in Fig.3a. After using STFPF method, the corrupted random noise was suppressed as shown in Fig.3b and the signal component was preserved.

Conclusion

In the present study, we introduce TFPF method to process MRS signals. For the characteristic of the MRS oscillating signal, we propose STFPF method. We concluded that the STFPF method proposed can effectively suppress the random noise corrupted in MRS signals. However, it should be recognized that the oscillating signals have a high nonlinearity and the IF estimations are biased. An appropriate window length should be selected to make the signal as close to linear as possible across the window length. To reduce the bias, the window length should be small, but only large window length can suppress the high level random noise. Therefore, high level random noise cannot be suppressed is the limitation of the present STFPF method. Solve this problem to apply STFPF method in MRS oscillating signal for high level random noise attenuation is ongoing.

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