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An Improved Spin Echo Train De-noising Algorithm in NMRL

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Abstract

Since the amplitudes of spin echo train in nuclear magnetic resonance logging (NMRL) are small and the signal to noise ratio (SNR) is also very low, this paper puts forward an improved de-noising algorithm based on wavelet transformation. The steps of this improved algorithm are designed and realized based on the characteristics of spin echo train in NMRL. To test this improved de-noising algorithm, a 32 points forward model of big porosity is build, the signal of spin echo sequence with adjustable SNR are generated by this forward model in an experiment, then the median filtering, wavelet hard threshold de-noising, wavelet soft threshold de-noising and the improved de-noising algorithm are compared to de-noising these signals, the filtering effects of these four algorithms are analyzed while the SNR and the root mean square error (RMSE) are also calculated out. The results of this experiment show that the improved de-noising algorithm can improve SNR from 10 to 27.57, which is very useful to enhance signal and de-nosing noise for spin echo train in NMRL.

Keywords

Nuclear Magnetic Resonance Logging, Signal to Noise Ratio, Spin Echo Train, Wavelet Transform

1. Introduction

Nuclear magnetic resonance (NMR) logging is a direct and effective technology for oil exploration that has been widely applied in petroleum well logging and rock core analysis since the 1990s when NUMAR introduced a reliable NMR logging tool to the oil industry. The hydrogen nucleus has a spin feature with different pore fluids and different relaxation characteristics. The porosity, T_2 spectrum, and other geological evaluation parameters of oil well information, which are very important in oil and gas explorations, are obtained through NMR logging [1,2].

Fig. 1 shows the hydrogen atomic nuclear processes around the direction of the static magnetic field B_0. The oscillating magnetic field B_1 must satisfy two conditions for effective interaction with atomic nuclear protons. These conditions are: (1) the oscillating magnetic field B_1 must have a substantial component perpendicular to the static field B_0, and (2) B_1 must have a frequency f equal to the proton's Larmor frequency f_0 in the static field.

In the case of a Carr–Purcell–Meiboom–Gill (CPMG) high-voltage pulse, the protons will process

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simultaneously with one another and may absorb energy from the oscillating field B_1, thus changing to a high-energy state. At the end of every high-voltage pulse, the protons will jump to a low-energy state and send out the energy signal (as shown in Fig. 2), then NMR will occur [3]. The energy signal, which includes the protons information of the measured object, such as effective porosity and longitudinal relaxation time T_2, is called the spin echo train, which is shown in Fig. 2.

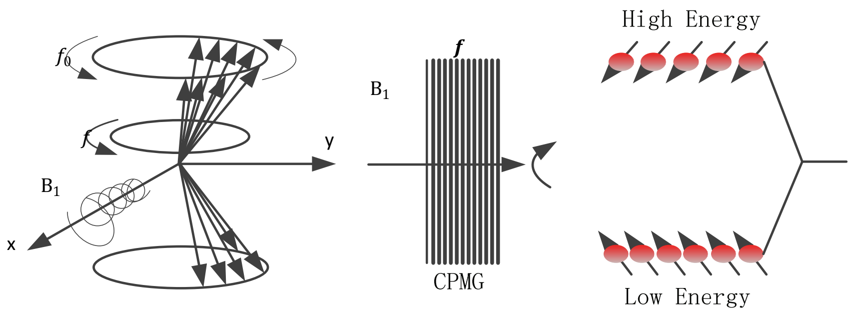

Fig. 1. The basic principle diagram of NMRL.

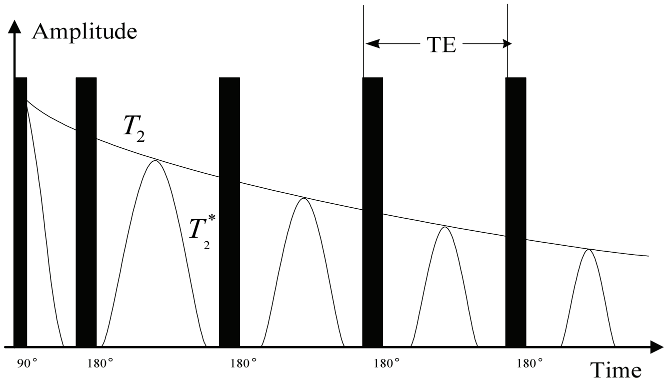

Fig. 2. The spin echo train in NMRL.

During the process of the NMR signal, most of these works are concentrated on the inversion algorithm. However, the amplitudes of spin echo sequence in nuclear magnetic resonance logging (NMRL) are small and the signal to noise ratio (SNR) is also very low. The direct inversion algorithm can lead to T_2 spectrum non-continuous or inversion instability, therefore, it is necessary to de-noising the spin echo train before T_2 inversion.

In engineering, there are many de-noising algorithms to deal with the spin echo train in NMRL. Veselinovic et al. [4] propose a group of wavelet filtering parameters to de-noise magnetic resonance image, through studying the based wavelet functions, the number of decomposition levels and the thresholds, which are involved in the process of dealing magnetic resonance images. The application of wavelet transform in medical NMR free induction decay signal was shown [5], comparing to study on these characteristics of the modulus value, shrinkage and translation invariant wavelet transform algorithm, this paper puts forward an improvement de-noising algorithm. A Stein of unbiased risk estimation (SURE) based on wavelet transform algorithm was discussed to de-noising the signals of

NMR [6]. In [7], an adaptive threshold filtering of wavelet method was used to de-noise the NMR signal, and the results shown that this adaptive method can get better effect, but the calculation of which adaptive threshold is very complicated.

According to these characteristic of spin echo train in NMRL, an improved de-noising algorithm based on wavelet transform and mean filtering method will been discussed in this paper. Then this improved de-noising algorithm will been designed based on its steps. To test this improved algorithm, a 32 points forward model of big porosity is build, the signal of spin echo sequence with adjustable SNR are generated by this forward model in an experiment, the results of this experiment and the conclusion will been shown in the end of this paper.

2. Improved De-noising Algorithm

According to Fig. 2, the amplitudes of spin echo train in NMRL are very small and the SNR is also very low. With multi-exponential decay characteristics of the spin echo train in NMRL, the flow chart of this improved de-noising algorithm is displayed in Fig. 3.

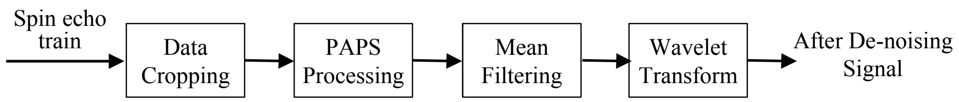

Fig. 3. The flow chart of this improved de-noising algorithm.

According to Fig. 3, the spin echo train first are cropped and the PAPS processing will be launched, then the mean filtering algorithm will be used before the process of wavelet transform, which with the improved soft threshold. The steps of this improved de-noising algorithm are shown as following:

Step 1: Data clipping

Because of the effect of the ringing, the first three data of the spin echo train have been mixed with a lot of randomness, which are usually defined as invalid data. Then the main work of this data clipping is taking out the first three data form the spin echo train.

Step 2: PAPS processing

In order to take off the random noise from the spin echo train, 0° and 180° phase incentive are used in NMRL, respectively. The process of PAPS can be described as the following formulas:

$$\begin{cases} S_1 = s + n \\ S_2 = -s + n \end{cases} \quad \Rightarrow \quad s = \frac{S_1 - S_2}{2} \tag{1}$$

where S_1 and S_2 are named as the spin echo train under the 0° and 180° phase incentive, respectively. n is marked as the random noise, the result of PAPS processing is shown as symbol s.

Step 3: Mean filtering

Many times PAPS processing are necessary, which can improve the SNR. In the improved de-noising algorithm, there are 16 times PAPS processing, the results of which are named as s_1, s_2, s_3, ..., s_{16}, then the mean filtering formula marked as

$$s = \frac{s_1 + s_2 + \cdots + s_{16}}{16} \tag{2}$$

Step 4: Wavelet transform with adjust threshold

The third part of this algorithm is wavelet transform with adjust threshold, choosing a right basic wavelet function and the number of hierarchical *j*, decomposing the NMRL signal after the mean filtering into coefficient and 1 to *j* detail coefficients.

The hard and soft threshold processing in wavelet transform are used widely in engineering applications, but there are some limitations. The hard threshold processing method exists in the transient signal peaks, the soft-threshold processing rule the signals too smooth. Based on soft threshold method and the advantages of hard threshold processing method, an improved method of threshold, which is defined as:

$$\hat{d}_{j,k} = \begin{cases} k * \text{sgn}(d_{j,k})(|d_{j,k}| - \lambda_j) + (1-k) * d_{j,k}, |d_{j,k}|, & |d_{j,k}| > \lambda_j \\ 0, & otherwise \end{cases} \tag{3}$$

where k is the factor, and $0 \leq k \leq 1$. When the $k = 1$ threshold processing method is actually a soft threshold. When $k = 0$ is a hard threshold processing. The symbol $d_{j,k}$ are named as the coefficient of each layer and the symbol λ_j is defined as $\lambda_j = \sigma_j \sqrt{2 \ln N}$, where N is the number of this signal and the symbol σ_j is marked as the standard noise deviation of the j layer. In this improved algorithm, the factor k is calculated as the following formula

$$k = \begin{cases} k = 0.9 & 0 \leq N \leq 100 \\ k = 0.75 & 100 < N \leq 200 \\ k = 0.35 & 200 < N \leq 300 \\ k = 0.1 & 300 < N \leq 400 \end{cases} \tag{4}$$

Step 5: Signal reconstruction

To constitute the after filtered NMRL signal, the main work of signal reconstruction is the inverse wavelet transform with the filtering layers of detail and the last layer approximation coefficients.

Step 6: End.

3. Experiments

According to these data from the rock analysis experiments with NMRI, a 32 points porosity modeling and the NMR signal with different noise were constructed in this paper. Then, four algorithms were used to deal with this signal of NMR in order to verify the advantage of the improved de-noising algorithm, which is also including the median filtering algorithm, the hard wavelet threshold filtering and the soft wavelet threshold filtering algorithm.

3.1 The High Porosity Modeling of 32 Points

The large porosity forward model is shown in Fig. 4, which adopts 32 points data in T_2 spectrum with the value of the relaxation time is from 0.5 to 2048 ms, and the value of the maximum porosity is 3.01. Fig. 4 shows the simulation signal of NMR with adjustable random white noise, which is generated by this large porosity forward model.

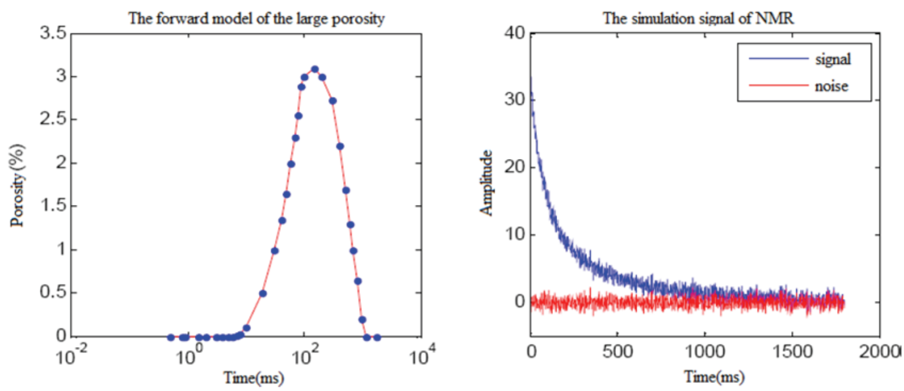

Fig. 4. The model of large porosity forward and the simulation signal of nuclear magnetic resonance with adjustable random white noise.

3.2 Comparison Analysis

Average filtering algorithm is a kind of typical low pass filter, which is conform to the characteristics of NMR signal. The wavelet soft threshold filtering algorithm uses 'dB6' decomposing 4 layers, while the hard threshold wavelet filtering algorithm also uses 'dB6' as the basic wavelet function for 4 layers decomposition.

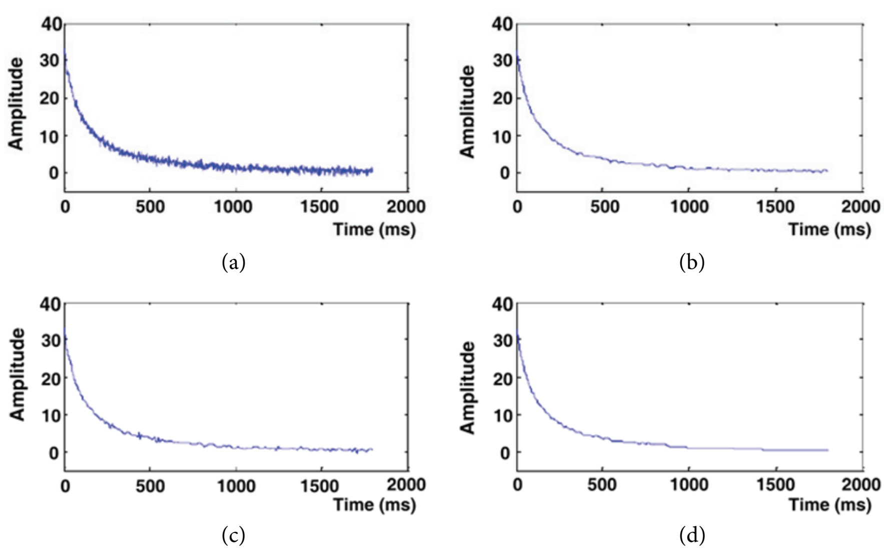

Fig. 5. Comparison of four filtering algorithms. (a) Average filtering, (b) wavelet soft-threshold filtering, (c) wavelet hard threshold filtering, and (d) improved algorithm.

In this improved algorithm, the NMR signal is divided into 64 windows and the impact factor is equal to 0.4. The results of four signal filtering algorithms as following in Fig. 5. From Fig. 5, it is obvious that there are many high frequency interferences in median filtering signal, as shown in Fig. 5(a). The wavelet soft threshold filtering signal is more smooth, but many smooth high frequency interference in the part of low signal amplitude, as shown in Fig. 5(b). Few peak burrs appear in Fig. 5(c), which uses the wavelet hard threshold filtering algorithm. In contrast, the signal in Fig. 5(d) is clean and smooth, which is processed according to the improved algorithm of filtering.

3.3 Signal to Noise Ratio and Calculation of Root Mean Square Error

Filtering effect of common parameters are SNR and mean square errors, the SNR and the root mean square error (RMSE) are defined as:

$$SNR = 10\log_{10}\frac{\sum_i |s_i^{'}|^2}{\sum_i |s_i - s_i^{'}|^2}, RMSE = \sqrt{\frac{\sum_i [s_i - s_i^{'}]^2}{n}} \tag{5}$$

The symbol s_i' is the filtered signal, the symbol s_i represents the filter before the signal contains noise signal, n as the length of the signal. Using four kinds of algorithms to deal with the filtered signal, and the signal to noise are shown in Table 1, the RMSE of four kinds of algorithms in Table 2.

Table 1. The SNR of four algorithms

NMRL	Median filtering	Soft threshold filtering	Hard threshold filtering	Improved algorithm
SNR=10	13.15	10.34	10.45	27.57
SNR=20	22.85	20.18	20.28	32.38
SNR=30	32.77	30.21	30.29	34.71

Table 2. The filtered signal RMSE of four algorithms

NMRL	Median filtering	Soft threshold filtering	Hard threshold filtering	Improved algorithm
SNR=1	1.5197	2.0642	2.0397	0.2833
SNR=2	0.4822	0.6561	0.6487	0.1523
SNR=3	0.1566	0.2072	0.2005	0.1229

Magnetic resonance imaging without having to filter the SNR is low, so only the data simulation of SNR is less than 30. From Table 1, the four algorithms of SNR can be analyzed. This improved algorithm can improve the SNR. In the first row of Table 1, After using a median filter algorithm noise ratio was 13.15, After using two thresholds for wavelet transform method SNR in turn was 10.34, 10.45, improved algorithm for filtering the SNR of 27.57, greatly improving the filtered SNR. From the data in Table 1, another conclusion can be analyzed that two thresholds for wavelet transform filter effect there is little difference.

Compared with other algorithms, this improved algorithm of mean square error is minimal. Smaller the RMSE, reflecting the filtered signal closer to the original signal, to prove the validity of the algorithm. According to the compared results from TableS 1 and 2, this improved de-noising algorithm not only improve the SNR of NMR signal, but also can effectively filter out the random noise.

4. Conclusion

This article intended for low SNR of NMR signal presents a modified filtering algorithm based on wavelet transform, which is a combination of mean filter algorithm with improved wavelet threshold filtering algorithm. The concrete steps are designed to improve filtering algorithms, based on hard threshold and soft threshold proposed an improved threshold function. Construct 32 large porosity modeling, and NMR signals generated by this model used for simulation, using median filtering and wavelet soft-threshold filtering, wavelets hard and improved threshold filtering algorithms for numerical simulation, after comparison of the simulation results and analysis, comparing and calculated the noise ratio of filtered signal and RMSE, as well as three algorithms in NMR spin-echo-string comparison are testimony to the effectiveness of the algorithm. As the result shows that this improved de-nosing algorithm is very suit to deal with the spin echo train in NMRL.

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