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Joint application of a statistical optimization process and Empirical Mode Decomposition to Magnetic Resonance Sounding Noise Cancelation

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ABSTRACT

The signal quality of Magnetic Resonance Sounding (MRS) measurements is a crucial criterion. The accuracy of the estimation of the signal parameters (i.e. E_0 and T_2^*) strongly depends on amplitude and conditions of ambient electromagnetic interferences at the site of investigation. In this paper, in order to enhance the performance in the noisy environments, a two-step noise cancelation approach based on the Empirical Mode Decomposition (EMD) and a statistical method is proposed. In the first stage, the noisy signal is adaptively decomposed into intrinsic oscillatory components called intrinsic mode functions (IMFs) by means of the EMD algorithm. Afterwards based on an automatic procedure the noisy IMFs are detected, and then the partly de-noised signal is reconstructed through the no-noise IMFs. In the second stage, the signal obtained from the initial section enters an optimization process to cancel the remnant noise, and consequently, estimate the signal parameters. The strategy is tested on a synthetic MRS signal contaminated with Gaussian noise, spiky events and harmonic noise, and on real data. By applying successively the proposed steps, we can remove the noise from the signal to a high extent and the performance indexes, particularly signal to noise ratio, will increase significantly.

1. Introduction

The method of Magnetic Resonance Sounding (MRS) is a non-invasive hydro-geophysical tool providing information on the distribution of water content in the subsurface and, under favorable conditions, hydraulic conductivity. A major limitation of the MRS technique is high sensitivity to noise. Beside the ubiquitous Gaussian distributed white noise (Costabel and Muller-Petke, 2014), the two important noise sources consist of power-line harmonics and discharges from both natural and man-made sources, that is, thunderstorms, telluric currents and magnetic storms, as well as electrical installations as cars, radio transmitters and electrical fences, etc. (Costabel and Muller-Petke, 2014; Dalgaard et al., 2012; Perttu et al., 2011). Short electrical discharges bring about an impulsive excitation of the band-pass filters with a subsequent near-exponential decay known as spikes (Dalgaard et al., 2012). The MRS signal usually varies between ten to a couple of thousand nV using 100 m square loop and the ambient noise is often higher (Perttu, 2011). Since the MRS signals are originally at nano-volt range, the ambient noise conditions will be very critical for them. In other words, MRS is vulnerably affected by even very low noises. In addition to this, the challenge of characterizing groundwater in some places by MRS is that the returned signals are quite weak due to low water content (Plata and Rubio, 2002; Walsh et al., 2012). Hence, it is vitally significant to implement de-noising on the MRS measurements. So for, several approaches have been developed for removing or at least decreasing the influence of noise during acquisition and data processing (Legchenko, 2007; Legchenko and Valla, 2002). Trushkin et al. (1994) proposed an eight-shaped loop in order to improve the signal-to-noise ratio. If the antenna with a figure-of-eight is used signal-to-noise ratio can be increased by a factor of 5 to 10 compared to circle or square loops. Using the same length of wire, the depth of investigation with the eight-shaped antenna is about a half of that the one acquired with the square loop (Bernard, 2007; Plata and Rubio, 2002). However, even with this loop the signal-to-noise ratio may be not sufficiently appropriate for inversion (Legchenko, 2007). Three filtering methods: block subtraction, sinusoid subtraction and notch filtering for removal of power-line harmonics from MRS measurements were studied by Legchenko and Valla (2002). They showed that, the notch filtering was the most effective but it distorts the signal of interest when the frequency offset between the Larmor frequency and one of the power-line harmonics is smaller than 8 Hz. In such conditions, subtraction techniques have preference. Also, a stacking procedure is utilized during data acquisition so that the signal-to-noise ratio increases $\sqrt{n}$ times, where n is number of stacks (Legchenko and Valla, 2002; Perttu, 2011; Plata and Rubio, 2002). But this process is, in fact, time-consuming. Plata and Rubio (2002) showed that interfering spikes cannot be considerably suppressed by stacking the signal records. Recent developments on hardware design allow overcoming some restrictions

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on applying MRS technique (Dalgaard et al., 2012; Dlugosch et al., 2011; Muller-Petke and Costabel, 2014; Walsh, 2008). Multi-channel devices use a primary loop for excitation and signal receiving, and a number of additional reference loops to simultaneously record the local noise. The references loops provide the possibility of mitigating the noise in the primary loop signal by subtraction through Wiener or adaptive filters (Dalgaard et al., 2012). However, the precondition for the use of adaptive noise cancelation using reference loops depends on the fact that the noise of reference channels has the best correlation with the MRS-signal detection channel. Besides Gaussian noise and power-line harmonics, MRS records may be contaminated by spikes. The conclusion of Dalgaard et al. (2012) observations illustrated that, the presence of spike makes adaptive noise cancelation useless and potentially unreliable. Jiang et al. (2011) suggested a statistical approach called the Romanovsky criterion to discern and discard spiky noises. Their procedure is performed in the stacking process prior to noise canceling. Costabel and Muller-Petke (2014) took advantage of the wavelet-like essence of spiky events to isolate and eliminate spiky signals in the wavelet domain. Moreover, they presented a remote reference based harmonic noise cancelation. They concluded that frequency domain (FD) is preferable to the time domain approaches. However, some drawbacks to the use of the FD method were observed by them. In spite of relatively successful application of the existing de-noising approaches, in our opinion a reliable and efficient technique to cancel both anthropogenic and natural electromagnetic noises from MRS measurements is still missing.

The general objective of this study is to use simultaneously advantages and characteristics of Empirical Mode Decomposition (EMD) (Huang et al., 1998) and a statistical optimization process (Shahi et al., 2011) to further enhancement of the signal-to-noise ratio in MRS signals. Despite EMD method offers many promising features for analyzing and processing geophysical data, there are still few applications on geophysics. Magrin-Chagnolleau and Baraniuk (1999) extract seismic time-frequency attributes through EMD method. Chen and Jegen-Kulcsar (2006) applied EMD in Magneto-telluric data processing. Jeng et al. (2007) use EMD for power-line interference and Gaussian white noise elimination from VLF-EM data. Battista et al. (2007) employ EMD to remove cable strum noise in marine seismic data. Han and van der Baan (2013) exploit EMD for seismic time-frequency analysis.

The paper is organized as follows. In Section 2, the methods and algorithms used in this paper are described. Next, in Section 3, we discuss the performance of the described methods in synthetic and real examples. A comparison of the results achieved by the proposed algorithm and SMAVOR software for the real data are presented in Section 4. A short conclusion summarizes the main ideas.

2. Methods

2.1. EMD algorithm

The recovery of a signal from observed noisy data remains a challenging problem in both signal processing and statistics. A number of filtering methods have been proposed, particularly for the case of non-stationary signals. Due to non-linear and non-stationary nature of the geophysical data (Mohebian et al., 2013) (e.g. MRS signals), use of an adaptive method for analysis of such data is absolutely necessary. EMD, as an adaptive method means that the basis is defined based on and derived from the data (Huang and Wu, 2008; Jeng et al., 2007), decomposes a signal into a set of mono-component functions called intrinsic mode functions (IMFs) (Huang et al., 1998). A mono-component function indicates an oscillating function close to the most common and basic elementary harmonic functions. Therefore, IMFs contain frequencies ranging from the highest to the lowest ones of the signal presented as amplitude and frequency modulated (AM–FM) signal, where AM carries the envelope and FM is the constant amplitude variation in frequency and computed through a sifting process. Any IMFs should satisfy the following two specifications:

1) The number of extrema (maxima and minima) and the number of zero crossings must either equal or differ at most by one.
2) At any given point, the mean value of the envelope defined by the local maxima and the envelope by the local minima should be zero.

The EMD algorithm for implementing sifting on MRS signal $e(t)$ is given as follows:

1) Identify all extrema (maxima and minima) of the signal, $e(t)$
2) Generate the upper and lower envelopes via interpolation among all the maxima and minima points, respectively (in our algorithm, we used Piecewise Cubic Hermit Interpolation).
3) Calculate the mean of the envelopes, $m(t) = (env_{up}(t) + evn_{down}(t))/2$.
4) Subtract $m(t)$ from the MRS signal to obtain the detail: $d_1(t) = e(t) - m(t)$.

Step 1 to 4 is one iteration of the sifting process. The signal $d_1(t)$ output of the first iteration is tested using the stopping criterion. Two possibilities now exist:

I. $d_1(t)$ is not an IMF (i.e. it does not satisfy the stopping criterion). In this case, $d_1(t)$ is given as input to the next iteration of the sifting process (i.e. step 1 to 4 is repeated)

II. $d_1(t)$ is found to meet the stopping criterion, so no further iterations are needed.

A stopping criterion to the number of sifting iteration is employed to insure that IMF component retain enough physical sense of both amplitude and frequency modulation (Chacko and Ari, 2012; Huang and Wu, 2008). Some stopping criterions are given by Huang et al. (1998). In our algorithm, the stiffing process is continued until a residue error of a standard deviation between consecutive components is met. The standard deviation between component d_{k-1} and d_k for k number of sifting iterations is given by

$$SD = \sum_{t=0}^{T-1} \left[\frac{|d_{k-1}(t) - d_k(t)|^2}{d_{k-1}^2(t)} \right], \tag{1}$$

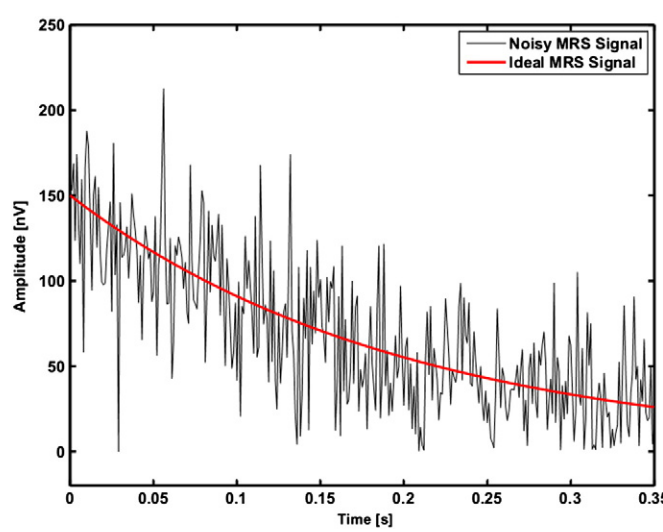

Fig. 1. Ideal (red) and noisy MRS signal (black) with SNR = 5.3 dB.