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Despiking of magnetic resonance sounding signals

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SUMMARY

In this paper a new method of removing spikes from magnetic resonance sounding (MRS) signals is proposed and investigated. We show that most spikes in MRS signals recorded with a Numis Poly instrument can be efficiently modelled as an impulsive excitation of a 4^{th} order bandpass filter. When the models of spikes are subtracted from the acquired signals an efficient reduction of noise is obtained. An example of the method is given using data from Norsminde, Denmark. The analysis shows that there is no correlation between the remaining noise in the primary coil and in the reference coils when powerline harmonics and spikes have been removed using our model-based approach. Directions for future research into optimized signal processing of MRS data are discussed.

Key words: Magnetic resonance sounding, noise reduction methods, noise models.

INTRODUCTION

It is well-known in the magnetic resonance sounding (MRS) community that a major limitation to the technique is the signal-to-noise ratio (SNR) which is often very low, see e.g. Behroozmand et al. (2015). Measurements can be heavily distorted by noise, in particular harmonic components from powerlines and impulsive noise, called spikes, from e.g. electrical fences. Various techniques are employed to improve on the SNR, e.g. figure-8 coils (Thrushkin *et al*. 1994), harmonic subtraction (Legchenko and Valla, 2008, Larsen *et al.*, 2013), and multichannel methods (Walsh, 2008). In the multichannel methods additional reference coils are used to measure the local noise field in the vicinity of the MRS measurement. Signal processing of the reference coil data results in a replica of the noise in the primary coil. The replica is subtracted from the signal and noise measured in the primary coil. Under optimum circumstances only the desired MRS signal is left and the SNR is increased.

However, multichannel MRS is not always able to provide the needed SNR improvement. One of the reasons for this problem is the fact that underlying the multichannel method is a tacit assumption that all noise sources, powerline harmonics, spikes and other noise components can be treated identically i.e. the exact same signal processing conditions applies to all noise sources measured in a given reference coil. This assumption is wrong when the sounding is carried out in complex noise environments with many sources, (Larsen, 2013). An example of the problem can be found in Figure 1. Here, an example of two spikes in a MRS multichannel measurement is shown. The top panel shows the signal in the primary coil and the next three panels show the simultaneous signals in three reference coils.

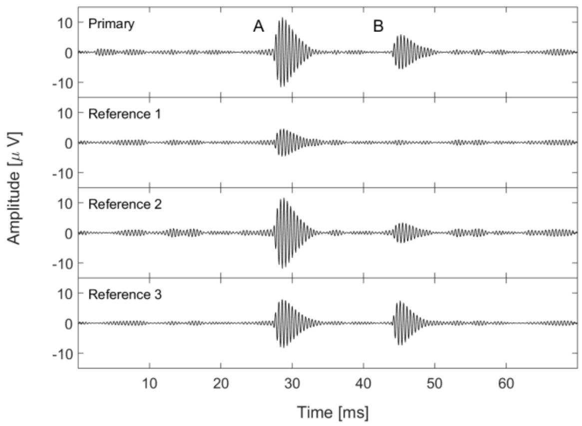

Figure 1. Examples of noise in MRS. Spikes are observed at A and B, but the amplitude ratios between the spikes are vastly different in the 4 channels. Figure adapted from (Larsen *et al.*, 2013).

In the primary coil signal the amplitude of the first spike is approximately twice the amplitude of the second spike, whereas in the third reference channel the amplitudes of the two spikes are almost identical. Even larger disparities in the spike amplitudes are seen in reference channel 1 and 2. The simplest explanation of the disparities in the spike amplitudes is that they originate from different sources with different distances to the four coils.

If one attempts a noise reduction of the primary coil signal by subtracting the signal in reference channel 3, the attempt will not be successful i.e. the gain setting that will efficiently remove the first spike will be inefficient for the second and vice versa. Similar considerations apply to the other two reference coils.

From the above example it can thus be concluded that efficient noise reduction of MRS signals warrants new advanced methods that can deal with complex multi-source noise environments.

As a first step in this direction we have recently proposed a model-based approach for removing one specific noise component *viz.* powerline harmonics (Larsen *et al.*, 2013). In this method a model, $h(t)$, of the noise from powerline harmonics is constructed

$$h(t) = \sum_{q=1}^{N} A_q \cos(q2\pi f_0 t + \theta_q).$$

The model utilizes that all harmonics are related to the fundamental powerline frequency. The model is fitted to the measured data and subtracted from these on a channel by channel, stack by stack basis. The method is often very successful in removing powerline harmonics. Subsequent to removing powerline harmonics, standard multichannel methods can be used in an attempt to further reduce noise, but as shown above this attempt can be unsuccessful if the noise field is too complex. In our current MRS processing scheme spikes are suppressed by identifying spikes with a threshold based decision algorithm. Segments of data containing spikes are discarded by setting the signal to zero here. However, this approach introduces discontinuities in the signal records that can distort the multichannel signal processing and introduce artefacts. Further valuable signal is lost by zeroing. In this paper we therefore propose and investigate a model-based method for removing spikes from MRS signals.

MODELLING OF SPIKES

The spikes shown in Figure 1 have been recorded with a Numis Poly from Iris Instruments. The instrument has a sampling frequency of 19.2 kHz and is equipped with a tunable hardware bandpass filter. The center frequency of the filter is set to coincide with the Larmor frequency. When impulsive noise is recorded with the instrument the noise is shaped by the bandpass filter. In the time domain the result is that $\delta(t)$-like impulsive noise is transformed into longer spikes. Careful inspection of the spikes in Figure 1 and Figure 2 reveals that a spike can be described as a carrier wave embedded in an envelope. The envelope has a rising edge with a duration of approximately 1 ms followed by a falling edge which disappears into noise after approximately 6-7 ms.

The simplest model that is consistent with the observed shape of spikes in an impulsive excitation of a 4th order bandpass filter. For an excitation that occurs a time t_0 with an amplitude A the source term is given by $A\delta(t-t_0)$. An analytical expression for a spike is thus

$$s(t) = Au(t-t_0)\left(e^{-a(t-t_0)} - e^{-b(t-t_0)}\right)\cos(\omega(t-t_0)+\varphi).$$

Here A is the amplitude of the spike assuming unity gain of the bandpass filter, $u(t)$ is the Heaviside step function, a and b are parameters describing the envelope of the spike and the parameters ω and φ describes the carrier frequency and carrier phase.

In total 6 parameters are used in the model of a spike and they can be determined by least squares fitting of the model to the recorded data. An example of a recorded spike is shown in Figure 2. Powerline harmonics have been subtracted from the data. The figure also shows the spike model fitted to the data. The model closely resembles the recorded data. Similar fitting results are obtained with typically more than 50% of the spikes found in our MRS data.

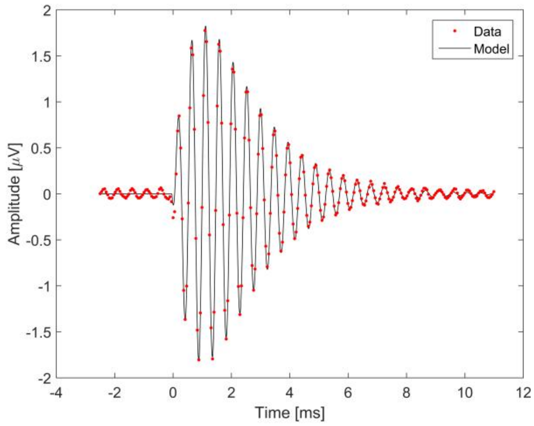

Figure 2. A short segment of an MRS noise-only recording containing a spike. Powerline harmonics have been removed and the proposed model (black line) has been fitted to the data (red dots).

Two examples of spikes that can't be described by the above model are shown in Figure 3. All spikes shown in Figure 2 and 3 are taken from the same data set recorded near Norsminde, Denmark.

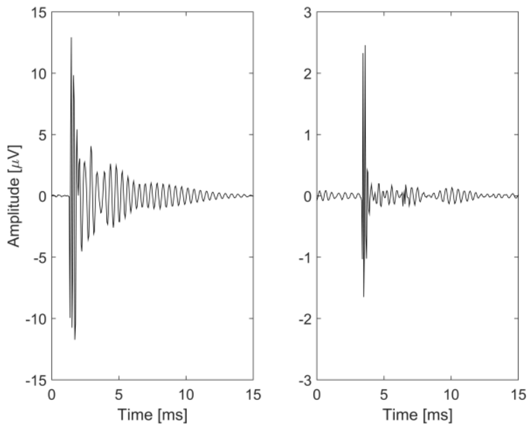

Figure 3. Two examples of spikes with complex shapes.

The presence of spikes with complex shapes warrants development of more advanced models and automated algorithms capable of distinguishing between different types of spikes and overlapping spikes. These issues will be pursued in future work.

SUBTRACTION OF SPIKES

In practice the spike model, $s(t)$, must be supplemented with a background term. All noise recorded with the instrument has been shaped by the bandpass filter and appears as an amplitude modulated signal with a carrier frequency equal to the center of the bandpass filter as seen from time $t=-2$ ms to $t=0$ ms in Figure 2. Similarly, the MRS signal oscillating at the Larmor frequency will also be fitted by the model. If the background noise and MRS signal are not separately accounted for, the model will also fit these components. Based on a heuristic approach the background, denoted $n(t)$, is modelled as

$$n(t) = (\alpha + \beta t)\cos(\omega t + \vartheta)$$

The linear term in the amplitude function accounts for decaying MRS signal and noise amplitude fluctuations. The parameters α, β, ω and ϑ are fitted to the signal immediately before and after the spike and the background model is interpolated during the spike.

The applicability of the method is tested using the Norsminde data set. For simplicity noise-only data with MRS signal is used. The top row of Figure 4 shows the recorded signals from the primary coil and a reference coil without any processing. The primary coil is single turn, square 100 m x 100 m, the reference coil is 7 turn 10 m x 10 m. A few spikes are visible in both time series. The far right panel shows the magnitude squared coherence function of the two signals in the region of interest around 2 kHz. The coherence function is very close to 1 at a number of powerline harmonic frequencies but is otherwise much lower.

The middle row shows the same signals after powerline harmonics have been removed. An additional number of smaller spikes are now visible in both channels. The peaks in the coherence function at the powerline harmonic frequencies have disappeared as these signals are removed. Around 2 kHz the coherence function has a value of 0.3 to 0.4. A much higher value, close to 1, is obtained if the coherence function is determined on short excerpts of the time series containing a single spike. This discrepancy is due to different linear relationships between spikes in the two channels when the spikes originate from different sources. The short term high coherence is averaged away when the coherence function is measured on a time series with multiple spikes.

In the Figures in the bottom row of Figure 4, spikes have been identified, modelled and subtracted from the two channels without visible distortion of the background signal. The coherence function of the noise reduced signals from the primary channel and reference channel shown on the far right is a key result of this work. There is a vanishingly small coherence between the remaining noise in the two channels. This implies that there is no correlation between the noise in the two channels and any attempt to do noise reduction using multichannel filtering will be unsuccessful.

CONCLUSIONS AND OUTLOOK

In the above paragraphs we have pointed out the need for more advanced noise reduction algorithms for MRS. The current algorithms are insufficient in complex noise environments. It has been shown how many spikes can be efficiently modelled assuming an impulsive excitation of a 4th order bandpass filter. Using model-based subtraction of powerline harmonics and model-based subtraction of many spikes we are now approaching a stage where two major components of MRS noise can be efficiently handled.

Further work on the method is in progress. The limitations of the technique, in particular the risk of over-fitting in the presence of MRS signal must be clarified. Techniques for dealing with complex shaped spikes and overlapping spikes are in development. Further we are currently investigating the improvements in signal to noise ratio that is possible with the method.

In the example given in Figure 4 it was found that the noise remaining in the primary channel and the reference channel after subtraction of powerline harmonics and spikes was incoherent. This result is somewhat unexpected and it remains to be tested whether this is a more general phenomena. At field sites with coherence between remaining noise components, better transfer functions can be estimated using spike-free signals and should lead to improved noise reduction.

The employed spike model has 6 free parameters that are fitted to each spike in each time series from each channel. The number of fitting parameters can be reduced in several means. For instance, t_0 is the same in all channels for a given spike and for spikes from a given source a fixed relationship between amplitudes and envelope parameters in the different channels can be expected. Further constraints on the fitting parameters might also be possible by incorporating prior knowledge of the bandpass filter.

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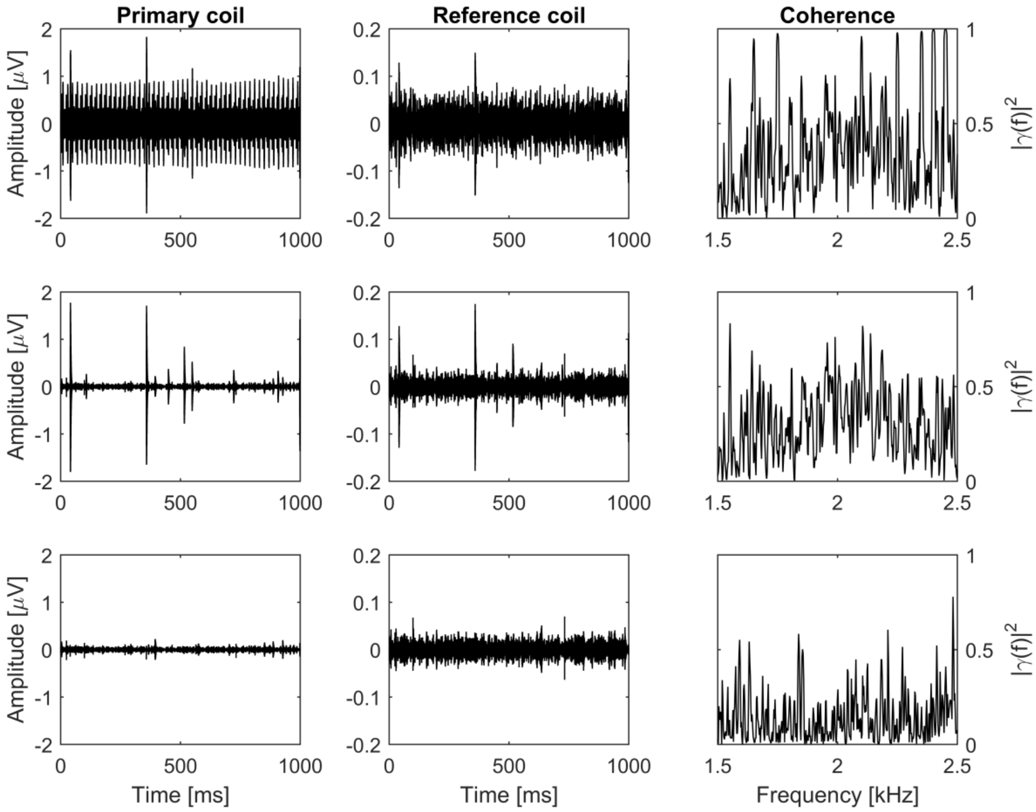

Figure 4. MRS, noise-only example from Norsminde, Denmark. All three rows show the signal in the primary coil (left), a reference coil (middle) and the magnitude squared coherence function between two signals (right). Top row shows raw signal. In the middle row powerline harmonics have been removed. In the bottom row spikes have also been removed.