INDUSTRIAL NOISE AND PROCESSING OF THE MAGNETIC RESONANCE SIGNAL

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INTRODUCTION

One of the major limitations of the magnetic resonance sounding (MRS) technique is its sensitivity to natural and man-made noise. Indeed, an alternating magnetic field produced by the precession of proton magnetic moments in groundwater varies between 10^{-12} and $4x10^{-9}$ T. The voltage created by this magnetic field (MRS signal) varies between 10 nV and 4000 nV when using a wire loop of 100 m diameter as a receiving antenna and, contrary to many geophysical techniques, the signal cannot be amplified by increasing the transmitter power. The frequency of the magnetic resonance signal (the Larmor frequency) is directly proportional to the magnitude of the geomagnetic field, and varies between 800 Hz and 2800 Hz around the globe.

ELECTROMAGNETIC NOISE GENERATED BY ELECTRICAL POWER LINES

A special field study was undertaken in order to learn more about industrial noise (Legchenko and Valla, 2003). The frequency range of interest for the MRS method is between 800 Hz and 2800 Hz, which corresponds to worldwide variations of the Larmor frequency set by the Earth's magnetic field. The study was carried out mainly in areas where the Larmor frequency is around 2000 Hz, but it is unlikely that this had any effect on the general nature of the results. The field data were recorded in France and abroad; the field data presented in this paper were acquired at three sites in France, one in Israel, one in the Netherlands and one in the USA.

A first appraisal of noise can be made by computing its amplitude as $\eta = \frac{1}{N} \cdot \sum_{i=1}^{N} \sqrt{X_i^2 + Y_i^2}$, where N is the number of samples in a noise record after the synchronous detector (channels X and Y). An example of noise measurements in France is shown in Figure 1. At each site, 40 consecutive 1000-ms-long records of the noise were made, at about ten-second intervals. The sampling rate was 2 ms, which makes N=500. It can be seen that even at the same test site the noise magnitude was not stable and can vary by a factor greater than two.

Industrial frequency stability is the keystone of power-line noise filtering techniques. In order to check the stability assumption, measurements were made of power-line harmonic frequencies in the investigated frequency range (37^{th} harmonic in Israel, 40^{th} in France, and 41^{st} in the Netherlands). It can be seen (Figure 2) that the frequencies vary from one record to another, but that instability is site-dependent, with the largest variations being observed in Israel. Such marked instability of industrial frequency is, in fact, very unusual and there is no clear reason why it occurs. However, even in the same country (France, Sites 1 and 2), the frequency estimates show a certain degree of instability (variations around 0.5 Hz and even higher), which can be explained partly by instability of the power-line fundamental frequency, and partly by noise influencing the accuracy of the estimation.

The proportion of 50 Hz harmonics in the noise spectra was also calculated (Figure 3). In order to diminish the spectral leakage effect caused by limited resolution of the Fourier transform on the accuracy of the estimation, the +/-1 Hz bandwidth around each harmonic was taken into account for the calculations. It was found that, depending on the site, the power-line harmonics represent only 20% to 50% of the noise energy within the +/-150 Hz bandwidth centred at about 2000 Hz. This high percentage of non-stationary noise observed in the vicinity of power lines may be explained by the fact that in the investigated frequency range, the most energetic (and probably more stable) lower harmonics are filtered out and only the higher harmonic numbers (20 to 55) are used. It is also possible that power lines, being long conductors, act as electromagnetic antennae and channel both man-made and natural electromagnetic noises from a large area, thus amplifying the grossly random background noise, especially on the vertical magnetic component that is measured with the MRS loop.

FILTERING TECHNIQUES

The efficiency of the well-known notch-filtering method was compared with the subtraction technique developed by Butler and Russell (1993) for processing seismo-electric measurements. This technique is capable of suppressing stationary power-line noise without distorting or attenuating the signal of interest. It involves subtracting an estimate of the harmonic component, with two different ways of estimating the component.

For practical implementation of the block subtraction method, it is assumed that the noise is regular and largely dominant over the signal (otherwise, filtering would not be needed) and, therefore, that non-stacked signal records are mostly noise. The strategy consists in selecting the time shift τ so that the noise sample *B(t)* from a noise record, and the sample *A(t)* that contains both signal and noise, are as similar as possible. An ideal sample rate would be an integer multiple of 50 Hz. However, the approach assumes stability and regularity, for at least a few seconds, of industrial noise generated by sources such as power lines.

The sinusoid subtraction technique is based on the representation of power-line noise as harmonics superimposed on the fundamental frequency (50 Hz or 60 Hz). The harmonic component is estimated from noise records and then subtracted from records containing both the signal and noise. The frequency of power-line harmonics, being relatively unstable, should not be determined by simply multiplying the fundamental frequency value by an integer number. During fieldwork, estimates must be made from the records, not only of the amplitude and phase of power-line harmonics, but also its frequency. When applying this technique to MRS signal filtering, it should be kept in mind that the harmonics farthest from the Larmor frequency f_0 are filtered out by the low-pass filter and do not influence MRS measurement accuracy. The few interfering harmonics (usually three, but sometimes five) are close to f_0. In the NUMIS system, synchronous detectors (3 or 5) are used for estimating power-line harmonics (amplitude, phase and frequency) using the non-linear fitting (Legchenko and Valla, 1998). For each synchronous detector, the reference frequency is set equal to one of the few fundamental harmonic frequencies close to the Larmor frequency: $f_{sd}^{k} = 50k$.

In order to complete the study, investigations were carried out on the efficiency of the notch filtering technique. This method is less sensitive to power-line harmonics instability, but introduces some distortion, the extent of which, for magnetic resonance records, depends upon the relative shift between the Larmor frequency and the harmonic frequencies, and also upon the relaxation time of the signal. When designing a low-pass filter for the MRS system, it should be kept in mind that the relaxation time of the magnetic resonance signal T_2^* varies typically from 40 ms to 400 ms and this determines the bandwidth of the filter. The Larmor frequency cannot be considered as constant, because it is affected by geomagnetic field variations within the volume investigated by MRS and also is unstable over time, and hence the bandwidth of the filter must be increased to about 4 Hz. The notch filter is centred on the power-line harmonic frequencies; as these are known only approximately, the filter cuts out +/-1Hz bandwidth around each harmonic. A combined filter, consisting of a low-pass filter centred on the Larmor frequency and a +/-1 Hz notch filter centred as close as possible to the harmonic of the fundamental frequency, is depicted in Figure 4 (dashed line). It should be noted that the notch filter removes between 3 and 5 harmonics, but they are not shown. Whilst the sinusoid subtraction method subtracts the estimates of power-line harmonics without distorting or attenuating the signal of interest, the notch filter always cuts out a narrow frequency band and, therefore, the signal may be deformed.

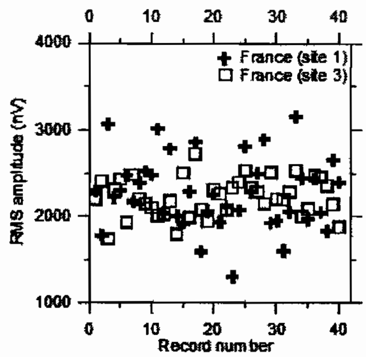

Fig. 1. Variations in the magnitude of power-line noise.

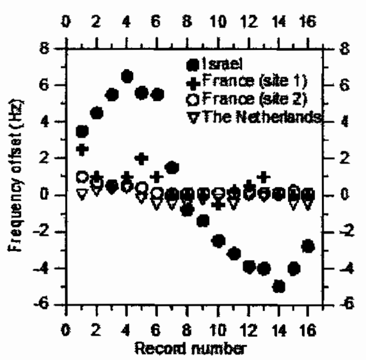

Fig. 2. Frequency of power-line harmonics.

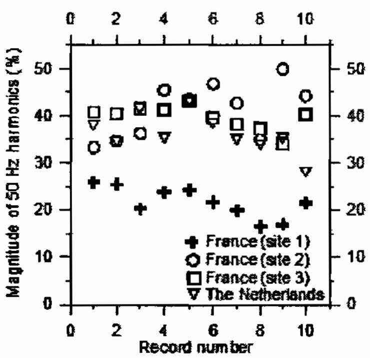

Fig. 3. Proportion of 50 Hz harmonics in the total noise.

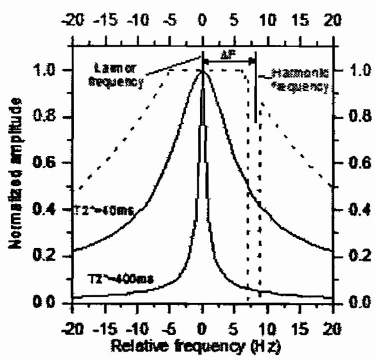

Fig. 4. Spectra of the exponential signal (solid lines) and combined low-pass and notch filter (dashed line).

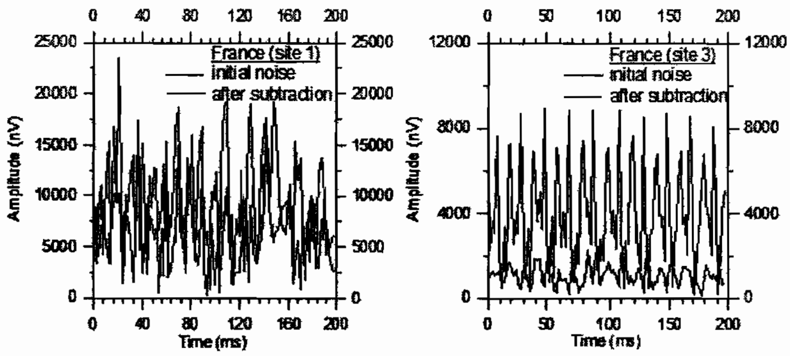

Fig. 5. Examples of the block subtraction application.

RESULTS

The efficiency of block subtraction can be demonstrated using two different noise records made in France (Figure 5). If the proportion of 50 Hz harmonics in the power-line noise recorded at Site 1 (about 20%) is compared with that of Site 3 (about 40%) (Figure 3), it can be concluded that the block subtraction method gives better results when the percentage of 50Hz harmonics (regular part) is greater. This conclusion matches exactly that of Butler and Russell (1993) concerning the efficiency of the block subtraction technique for the 0.1-1000

Hz frequency range. Independently of the filtering technique, the efficiency of the noise filtering depends on the test site. The best results are obtained at sites where the noise contains the largest percentage of 50 Hz harmonics. At the same site, notch filtering appears to be the most efficient for noise reduction as it cuts out the largest bandwidth. The sinusoid subtraction and the block subtraction are respectively less efficient. However, it should be remembered that when the Larmor frequency is close to one of the power-line harmonic frequencies ($\Delta F \rightarrow 0$), notch filtering might also distort the signal of interest. So, depending on the noise and the frequency offset, a compromise must be made between removing the noise and keeping the signal undisturbed so that signal parameters can be estimated. Based on experience gained to date, the rule for selecting the filtering method is proposed in Table 1:

Filter	T_2^*=100 ms	T_2^*=200 ms	T_2^*=400 ms
+/-1 Hz notch filter	ΔF>4 Hz	ΔF>6 Hz	ΔF>8 Hz
Sinusoid subtraction	ΔF<4 Hz	1<ΔF<6 Hz	2<ΔF<8 Hz
Block subtraction	ΔF<1 Hz	ΔF<1 Hz	ΔF<2 Hz

Table.1. Rule of selection for the filtering technique.

Figure 6 shows NUMIS records (after the synchronous detector) made with the same value of the pulse parameter containing both the signal and the noise with a different number of stacks and different filtering. It can be seen that application of notch filtering allows signal recovery using 10 stacks with about the same degree of accuracy as using 200 stacks without notch filtering.

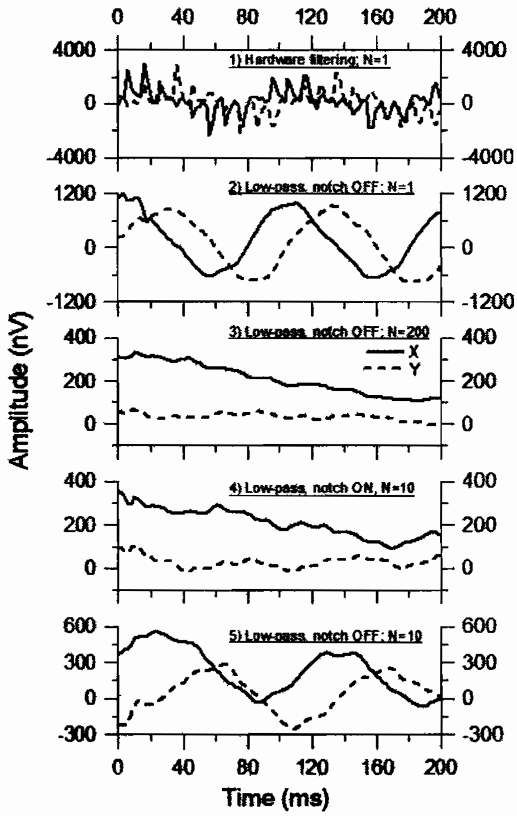

Fig. 6. Field example: filtering of signal records.

CONCLUSIONS

As the percentage of 50 Hz harmonics in the power-line noise is site dependent, the efficiency of filtering schemes based on the assumption of noise stability and regularity are also site dependent; the more regular the noise, the more efficient is the filtering. Three existing filtering methods; block subtraction, sinusoid subtraction and notch filtering were applied to magnetic resonance records. It was found that notch filtering was the most efficient, 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 this case the subtraction techniques are preferable.

REFERENCES

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