Introduction

The surface nuclear magnetic resonance (SNMR) method is gaining momentum as an efficient tool to non-invasively detect, map and quantify groundwater resources and estimate the hydraulic characteristics of the subsurface (Heirtrich et al., 2007 ; Behroozmand et al. 2014). However, one of the biggest challenges inherent to the method is related to the need of achieving a satisfying signal-to-noise ratio. This is frequently difficult due to the relative weakness of the signal (hundreds to thousands of nV) compared to the EM noise level, which can often be several orders of magnitude higher. The amplitude of the EM noise is very site-dependent since it variates depending on the type of EM noise sources surrounding the study location, but also on the precise position of the acquisition loop within these noisy EM fields.

One of the most commonly encountered EM perturbations in anthropic environments is the so-called harmonic noise, produced by power-lines, which consists of the harmonic EM signals associated with the fundamental frequency of the transmission power-lines (railway, electrical distribution network or pipelines). This type of EM noise generally exhibits a very high amplitude and must therefore be removed from the acquisition signal otherwise the SNMR data cannot be retrieved nor processed. To do so, several techniques have been developed. Butler & Russell (1993) first presented and compared the methods of block subtraction and sinusoid subtraction applied to the removal of harmonic noise in seismo-electric records. Later, Legchenko & Valla (2003) applied these techniques in the context of SNMR acquisition signals, and also compared them to the notch filtering approach. Both studies agree on the fact that the block subtraction method loses efficiency when the percentage of harmonic noise in the signal decreases, which can be problematic in complex noise environments. The main drawback of the notch filtering approach is that the SNMR signal gets distorted if the Larmor frequency is close to one of the harmonics frequency ($\Delta f < 8Hz$), at which point a compensation procedure must be applied, which adds uncertainty to the filtering process and to the SNMR parameters estimation. Since then, the SNMR community has been developing other methods for harmonic noise cancellation (e.g. Hein et al. 2017) or improving existing ones (Jiang et al., 2011). In particular, Larsen et al. (2014) provide developments of the sinusoid subtraction method to which they refer to as the model-based subtraction technique. This efficient approach has then been implemented to process harmonic noise in the open-source code MRSMatlab (Muller-Petke et al. 2016).

In this paper, we investigate how the efficiency of the model-based approach can be severely deteriorated when the harmonic noise characteristics differ from the usually assumed conditions (single noise source with constant fundamental frequency over the duration of a record). We introduce a new frequency estimation approach to adapt to more complex conditions (multiple noise sources and varying fundamental frequency). In the first section, we use synthetic data to investigate the case where two noise sources of different fundamental frequencies (railway and electrical network) contaminate simultaneously the acquisition signal. In the second section, we introduce the Nyman and Gaiser estimator derived by Saucier et al. (2005), and adapt it to address the issue of harmonic noise whose fundamental frequency variates within the acquisition duration. We demonstrate the efficiency of the method with both synthetic and real data.

The model-based subtraction approach and frequency estimation

This method is based on subtracting from the acquisition signal an estimation of the harmonic noise components that is obtained through a non-linear fitting process. The generally accepted model for harmonic interference is given by Larsen et al. (2014) as:

$$h(k) = \sum_{m} A_m \cos\left(2\pi m \frac{f_0}{f_s} k + \phi_m\right) \qquad (1)$$

where $h(k)$ denotes the harmonic model sample at time k, A_m and ϕ_m are the amplitude and phase of the mth harmonic component, f_s is the sampling frequency and f_0 is the fundamental frequency of the harmonic noise signal. The objective of the model-based approach is to determine the harmonic model that best reduces the energy of the acquisition signal. It is done by solving the following optimization problem.

$$\|SNMR - h\| \to min \qquad (2)$$

where $SNMR$ denotes the acquisition signal and h the harmonic model. If the fundamental frequency f_0 of the harmonic noise is known, equation (2) reduces to a linear problem and can be solved in a straightforward way.

The nominal value of f_0 for electrical network power-lines is typically supposed to be 50 Hz in Europe (60 Hz in North America), whereas for railway power-lines, f_0 has a nominal value of 16.66 Hz. However the true fundamental frequency value is never exactly the nominal value, because some fluctuation in time happens due to variations of power demand and supply. Adams et al. (1982) reported variations that can reach 0.03 Hz in a matter of minutes. Legchenko & Valla (2003) also report site-dependent instability of the 50 Hz power lines fundamental frequency in Europe, estimating variations up to 0.5 Hz between several records. Because of this, equation (2) remains a non-linear optimization problem, with f_0 being the single non-linear parameter. To address it, Larsen et al. (2014) propose to determine f_0 by solving several times the linear problem while running through an optimized grid search, and chose the frequency value that yields the best signal reduction. This approach gives satisfying results in the presence of one harmonic noise source with constant frequency, although the processing time becomes quite significant with large data sets (several hours).

Another method to estimate the fundamental frequency of harmonic noise was presented by Saucier et al. (2005), although not in the specific context of SNMR studies. Their method is based on the Nyman and Gaiser estimation (NGE) technique that was initially proposed for the processing of seismic records (Nyman and Gaiser, 1983). Saucier et al. (2005) adapted the NGE method to construct a single lower variance estimator of the fundamental frequency. We adapted the Saucier estimator to the processing of SNMR data and observed that harmonic cancellation could be performed with equivalent efficiency and reduced computing time by a factor of 2 compared to the grid-search approach, using the coarsest grid possible, and a factor of 7 when using a more refined grid-search such as done in the MRSMatlab code (Muller-Petke et al., 2016). In the following investigation, both methods were used alternatively depending on the context, and are referred to as the NGSE approach (Nyman, Gaiser and Saucier estimator), or the grid-search approach.

Two different fundamental frequencies

The first case that we investigate relates to the situation where the SNMR study is taking place at a location nearby both a railway powerline and an electrical network powerline. These two noise sources can then contaminate the acquisition signal with two harmonic signals, each having a different fundamental frequency value (nominal values of 16.66 Hz and 50 Hz, respectively). If these two values were not related, the harmonic noise cancellation could be easily done by removing sequentially one of the harmonic signal, and later on the other one. In this particular case however, the problem originates from the fact that the railway frequency was chosen so as to be one third of the global electric network frequency. It follows that, from a Fourier space point of view, for each frequency that is a multiple of 50 Hz, the railway harmonic signal will overlap the electrical network harmonic signal. In addition, this overlapping effect might not be "perfect" since each harmonic signal will be slightly deviated from its nominal value, which will produce "double" or "bended" frequency peaks such as those presented on Fig. 1a) and 1b), respectively (produced using synthetic data).

Synthetic harmonic noise was generated to evaluate the capacity of the classical grid-search approach to adapt to this situation. As shown on Fig. 1c), the sequential removal of the two harmonic signals, i.e one fundamental frequency after the other, fails to remove completely the harmonic noise at frequencies multiple of 50 Hz. To achieve satisfying cancellation, it is necessary to proceed to a *simultaneous* removal of the two harmonic signals, which implies solving the non-linear problem of equation (2) with two non-linear parameters (the two different frequencies). Here, this was done through a 2D grid-search, which produced excellent cancellation, although a very important increase in computing time (factor of 30).

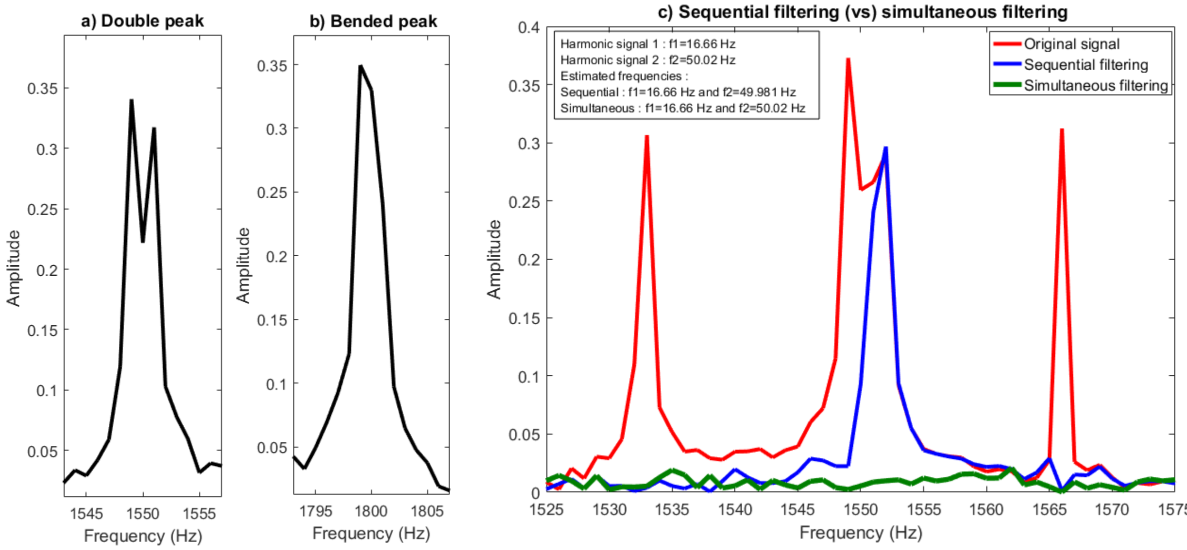

Figure 1: *Synthetic harmonic noise data with random amplitudes and phases, 5% Gaussian noise, are shown in the Fourier domain to illustrate the issues raised by the presence of two different fundamental frequencies (16.66 Hz and 50.02 Hz) within the harmonic noise. Fig 1a) and 1b) show "double" or "bended" frequency peaks that can appear at frequencies multiple of 50 Hz. Fig 1c) shows the comparison between a sequential removal of the harmonics (50 Hz then 16.66 Hz) and a simultaneous removal performed using a 2D grid-search model-based cancellation scheme.*

Quickly varying fundamental frequency

For most harmonic processing schemes, a common assumption is to consider that the fundamental frequency of the harmonic noise signal does not vary significantly over the time duration of the acquisition (e.g Legchenko and Valla, 2003 ; Larsen et al. 2014), which is usually on the order of 1s. In many cases this assumption is valid and the processing scheme remains effective. However, a too quick or too strong variation of the fundamental frequency value within the record duration can often be the main cause for poor efficiency of harmonic noise cancellation. Indeed, in a similar manner as previously, such a variation will result in the appearance of double or bended frequency peaks in the Fourier domain, as shown by the real noise data example presented on Fig. 1a). Facing these, a one frequency processing scheme such as NGSE or the grid-search approach will fail (Fig.1b). However, in this case, the harmonic noise can be effectively removed by sampling appropriately the acquisition signal, applying independently the NGSE approach to these samples and reconstructing the acquisition signal. Fig. 1b shows the results of applying this "bootstrap processing" approach on real whose frequency structure suggests a strongly varying fundamental frequency. The classical one-frequency grid search fails to remove the strong harmonic peaks, whereas the "bootstrap processing" approach removes them efficiently.

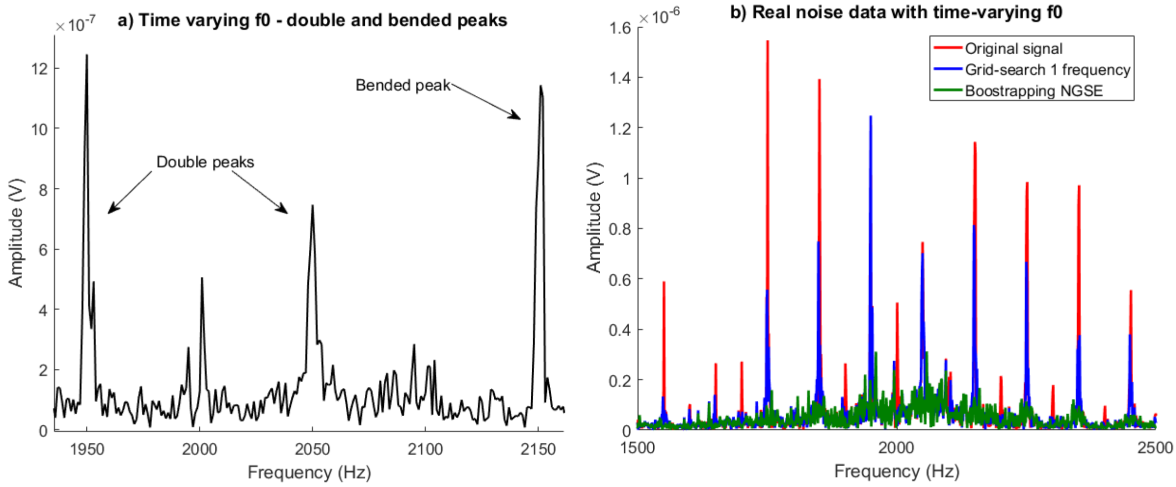

Figure 2: *Real noise data acquired at the Larzac plateau, France, with a 40m diameter circular loop. Fig 1a) shows "double" or "bended" that is likely due to a quickly varying fundamental frequency. Fig 1b) shows, for the same data, with a larger frequency range, the comparison between the use of an optimized grid-search for 1 frequency, with the use of the bootstrapping approach and NGSE method.*

Conclusions

In complex noise environments, the processing of harmonic noise needs to be adapted to the particular situation in which the SNMR study is performed. Different contexts such as (1) multiple fundamental frequencies or (2) quickly varying fundamental frequencies can cause the classical harmonic processing schemes to fail. In the first case, we show that the non-linear problem must be solved simultaneously for the two fundamental frequency values, which increases the computing time. To adapt to the second case, we developed a new processing scheme based on a bootstrapping approach coupled with the Nyman, Gaiser and Saucier estimator (NGSE). New processing schemes such as the bootstrap harmonic processing presented here need to be developed. From one hand to allow the processing of SNMR data embedded in complex noise signals, but also as predictive tools to study the noise characteristics at a specific location, and hence anticipate the most adapted processing strategies.

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