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Improvements in the Measurement System of a Biological Magnetic Induction Tomographical Experimental Setup

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Abstract. Magnetic Induction Tomography (MIT) is an imaging technique that allows mapping the internal structure complex conductivity of a body. In this paper a feasibility study to implement a higher resolution MIT system for biological tissues is carried out. Recent improvements in measured signal stability and accuracy as well as a much improved angular resolution measurement of the multi-coil setup are presented which, together with a new mechanical design allows obtaining longer stable and more accurate acquisitions. This allows improving the number of measurements without trends or external perturbations, leading to a better conductivity resolution and to an enhanced image reconstruction. Throughout the paper experimental data is used to consolidate results.

1. Introduction
Magnetic Induction Tomography (MIT) [1, 2, 3] is an imaging technique for passive electrical properties by measuring an induced magnetic field generated inside the body in analysis by an externally imposed magnetic source, allowing reconstructing its internal structure. In the case of biological tissue bodies, the major electrical property to be characterized is the complex conductivity. Bodies to be analyzed have some tens of centimeters, characterized by small changes on conductivity between adjacent tissues, typically 0.5 to 2 S/m. Frequencies ranging from some tens of kHz to some MHz are used in the excitation magnetic field. Most recent MIT setups are mechanically static with several sensor coils and source coils mounted in a cylindrical wall around the object [1, 4, 5]. Measurements are taken in a short period of time using a fixed short number of sensing and source coils (typically between 8 and 16) in order to present an in-vivo real time image. The idea of the presented project is to study the feasibility of a high resolution system, relaxing if necessary the in-vivo demanding. In this sense, more measurements with more incident angles between the source magnetic and the body in test should be used in order to improve the image reconstruction. For that, measurements should be stable for a longer period of time. A prototype that allows moving sensing coils, to rotate and to move the body vertically was developed in order to study an optimum set of measurements for each body in analysis. In previous work we developed a new cancelation technique called Twin Coils Setup [6], which is being further enhanced in this paper. Its novelty consists in placing the source at the center of a circular setup, and the sensing coils positioned at opposite sides of the circular layout. The half circle where the object is placed is then measured differentially. In figure 1,
a photo of the new setup is shown. It has several advantages over the classical circular setup:

(i) the sensor position error due to movement is not so critical as in the case of a standard setup; (ii) the carrier amplitude does not vary considerably along positions, meaning that due to its symmetry no position is preferential. Finally, (iii) it allows for differential measurements for better excitation field suppression, as is the case of planar gradiometers [5], but it does not generate ambiguous conductivity spots with symmetric values which is one of the gradiometers drawbacks [5]. However it is intrinsically noisier since the differential signals are not in the same PCB as the planar gradiometer.

1.1. Measurement Challenges
The vector field $\Delta V/V$ called signal-to-carrier ratio (SCR), relates the voltage induced in a sensing coil by the body induced magnetic field ($\Delta V$) with the voltage induced in that sensing coil by the magnetic source field ($V$). It is intended to be a system performance indicator. In biological tissue measurements, SCR absolute value should be in the order of $10^{-7}$ [5].

The residual signal ($V$) corresponds to the resultant signal after adding the two sensing coil electromotive forces. An in-vivo acquisition system for MIT, like the one described in [7] needs only to be stable for some seconds or less. In this paper we have the goal of creating a stable noise base for several minutes in order to acquire data from several magnetic field incidence angles and body positions. Measurements from each sensing coil geometric position should be equally stable, which imposes stringent requirements in noise stability for an interval of residual amplitude values. To understand the measurement requirements for image reconstruction it is described the implemented experimental acquisition scenario for this setup. If a 1.5 A current at 870 MHz is fed to a coil source, it will induce an electromotive force of 315 mV at each coil. Distance between sensing coils and the source is equal to the sensing circle radius, which is 20 cm. Source coil has 5 cm while the sensing coils have 3 cm diameter. Looking to the necessary SCR value ($10^{-7}$), it is necessary to have a noise standard deviation in the order of magnitude of 30 nV. For the case of the twin sensing coils, the system should be stable for residual signal amplitudes ($V$) between 10 $\mu$V to 400 $\mu$V which are the residual amplitudes found experimentally when rotating the sensors. In previous work done with gradiometer sensors the resulting signal was stabilized during a small time frame since drifts and measurement perturbations are referred to be an issue for long time acquisitions [7]. Furthermore, it has a cancelation factor much more dependent on its position, making it more difficult to be used in a moving system. Typical values are even divided in far and short distance sensing gradiometers. Presented standard deviation for far distance is 300 nV absolute value and the same quantity for short distance is 4360 nV. The twin setup doesn’t make this distinction since distances are the same for all sensors. An older publication from the same authors presents higher stability values, between 10 and 80 nV [8] lacking, however, information about the amplitude of the applied current and the long time drift problems are also referred. In our previous paper, a minimum $10^{-5}$ SCR absolute value
was obtained for a long time acquisition interval (more than 1 minute at least), corresponding to 2000 nV standard deviation instability for similar conditions. Source current drifts that generate drifts in acquired signals were the main noise source, besides thermal noise and electromagnetic noise. In this paper, we present our recent work done on acquisition electronics, electromagnetic shielding and signal processing in order to be able to stabilize acquisition during a longer time frame, improving the allowed SCR to be acquired and the corresponding image reconstruction quality. A minimum residual standard deviation value of 30 nV for a 75 point average sliding window was obtained for all coils, corresponding to $10^{-7}$ SCR value for a long time acquisition frame (> 5min).

2. Setup Description and Measurement Method

The prototype is made up of 8 sensing coils and one source coil. The sensing coils can rotate around the source coil about 45, taking any desired angular position in this interval. Since sensing coils are separated by the same angular value, all angular space is covered by them. Each pair of opposite sensing coils is directly connected at a pre-amplification circuit input. The coils could be mechanically positioned in order to obtain the least residual signal possible for each sensing coil pair. The mechanical system is made in a PVC material, electrically and magnetically inert and there are no metal structures in an approximately 1 m diameter around the source coil. The used source current is a 500 mA amplitude sinewave at 870 kHz.

2.1. The Sensing System

Each acquisition channel that corresponds to a twin coil pair is presented in figure 2. Sensing coils are connected to differential shielded cables that are grounded at the pre-amplifier stage. Inside each shielded cable, the differential cables are twisted in order to reduce magnetic induction. Two differential wires, each coming from a distinct sensing coil of the twin pair, are short circuited in order to subtract the electromotive forces. Careful has been taken in creating symmetric paths for each twin coil signal, before having them added. Electrical capacitance shields based on orthogonal combs were applied to each coil. Since electrical disturbances in the source are not a common mode perturbation in the twin pair, if this effect is not well cancelled it will be present in the residual signal as disturbances. The signal is fed into a differential amplifier with variable gain between 2 to 130. A 4th order low pass filter, centered in 1100 kHz is used to reduce the second harmonic amplitude and avoid saturating the ADC input. The ADC system used is a PXI 5105, with 12 bits, up to 60 MS/s and 8 simultaneous sampling channels, using the lowest distortion input range, 200 mV peak to peak.

2.2. The Signal Processing for Measurement Improvement

Signal processing technique used over acquisition should be able to estimate stable values for amplitude and relative phase, which are the major information for the reconstruction process. This could be improved by using averages over a large number of samples to reduce the signal standard deviation. In this sense, it was chosen a fast method to process acquired data. The Goertzel Transform is an efficient method to calculate one DFT coefficient using an efficient second order IIR filter [9]. In order to choose the frequency bin to measure, an interpolated
IpDFT is used. Then a set of three bins are calculated using the Goertzel Transform, the IpDFT bin and their two neighbor bins. Then just the bigger is taken. This method is faster than the FFT if the number of processed bins is inferior to log2(N), where N is the number of points (typically 450k points). Since here we take three bins to process, this is a good method for N > 8. For the referred number of points, Δf is approximately 15 Hz. To choose the exact number of points to avoid leakage and bound the significant power in a unique bin, an a priori experimental optimization of the necessary number of points is done. The size of this truncated window is calculated just once because its change modifies the bin frequency interval and hence, the acquired signal and noise power. Despite the fact that the leakage effect is never completely cancelled, we are able to minimize leakage and guarantee that at least 98% of it is contained in a single bin. Limiting measurement to just one bin makes the SNR the best possible from the spectrum measurements. After analyzing the output signal from the twin sensing coils when the source current is applied, it was found that the chosen bin amplitude and its phase is modulated by approximately a 50 Hz frequency signal with an amplitude that is strongly linear with the applied current. For 500 mA source current signal, this modulation has approximately 17 μV of amplitude. Moreover, it was verified that this modulation was not found in a scenario without applied currents. In order to reduce this we applied an initial sliding window that allows finding an integer number of 50 Hz periods to be acquired. Just after this, the correct number of points to avoid leakage is applied and the final Goertzel transform is applied to the truncated array, averaging an integer number of 50 Hz periods of the modulation wave.

2.3. Instabilities
Several instabilities were identified. (i) Firstly, the current amplitude has long term trends that are larger for larger currents. Since the ratio between current and the induced signal in sensing coils is constant, which was confirmed experimentally, drifts in sensing coils are proportional to drifts in current. Moreover, since the measured voltage V is the residual of the sum of the induced signals from each twin coil, its amplitude is also proportional to the current amplitude change. Three linear compensation methods were tested: Principal component analysis (PCA), a Linear Compensation method based on the relation source current residual amplitude and a Correlation based compensation method. It was found that the best results were given by the PCA method [9]. All results are presented using this method. (ii) The second type of instability has to do with non cancelled electric capacitance effects. As previously mentioned, since the voltage generated by the capacitance between the source coil and the sensing coils have the same signal in both coils, it is not in the common mode of the differential pair. Again, using the PCA method between each channel and a reference twin coil pair, it is possible to extract the non common mode signal. However, the relevant signal from the object in analysis is correlated between the pairs of coils and significant loss of signal can occur if any two coils pairs are related. Experiments using as reference coil the orthogonal twin coil pair were taken. This pair is theoretically unaffected by the object when no movement is taken. (iii) Finally, thermal drift in the acquisition electronics was identified. Experimentally, in order to avoid large thermal trends, some warm-up time was allowed before making any measurements. After that, circuits were able to be more balanced thermally, typically changing 0.2 C maximum. For this level of temperature change, no direct relation with amplitude or phase changes was identified.

3. Results
The resulting electronics spectral noise density is dominated by the amplifier stage noise (for large gain), since filter noise and the PXI noise are added to an amplified signal (Gain between 90 and 100). Theoretical input noise of the system is the amplifier input noise 35 nV/√Hz. Experimental standard deviations over the 870 kHz DFT coefficient (Δf = 15 Hz) using the referred signal processing method are now analyzed. In the next table it is presented the PXI
alone in short circuit, the PXI with the Pre-amp in short circuit, and all of the acquisition system for a twin coil pair:

| Table 1. Experimental standard deviation of a twin coil pair |
|----------------------------------------------------------|
| Noise Value at 870 kHz bin / nV | PXI | PXI+Preamp | PXI+Preamp+Twin Coil pair |
|-------------------------------|-----|-----------|--------------------------|
| Noise Std. Dev. at 870 kHz bin /nV | 1000 | 200 | 300 |

3.1. Stability Results
To show the performance of the defined signal processing and of cancelation methods, in the next figure are presented 300 seconds acquisition. Three signals are presented, a signal without any compensation, the same signal after PCA current compensation and the same signal after PCA current and reference coil compensation. These results could be compared by the respective standard deviations, presented in table 2, where the corresponding minimum measurable SCR is presented.

| Table 2. Experimental standard deviation of a twin coil pair |
|----------------------------------------------------------|
| No Comp. | Comp. Current Signal | Comp. Current Signal and Ref. Coil | SCR Abs. Value |
|---------------|---------------------|-----------------------------------|----------------|
| Amplitude σ / nV | 3290 | 821 | 298 | 2.8 · 10⁻⁶ |
| Amp. σ from sliding window /nV | 3294 | 532 | 79 | 7.3 · 10⁻⁷ |
| Phase σ /m | 170 | 6.8 | 5.6 | - |
| Phase σ from sliding window /m | 164 | 4.1 | 1.4 | - |

The standard deviations orders of magnitude are consistent and repeatable. Compensation extracts trends from the signal creating a stable white noise. This explains the low values for standard deviation using the sliding window mean after applying the compensations.
Increasing the number of acquisitions could lead us to an optimum measurement scenario where measurement standard deviation could be sufficiently reduced to obtain the desired minimum measurable SCR. The minimum obtained standard deviation was 30 nV for a 75 window which gives an SCR of $2.7 \cdot 10^{-7}$. In a final acquisition process compensations are done by controlling the current constantly, even when the object and the sensing coils are moving. Each acquisition and amplitude and phase calculations take about 250 milli-seconds but improvements on this can however be done in order to take more acquisitions per second.

3.2. Conductivity Measurements

First acquisitions using the described methodology was done for biological conductivity objects using small cylindrical conductivity disturbances displaced along Y and Z axis, along the lower half of the central plane, as indicated in figure 4. In figure 5 two imaginary component maps of the received signal, which are related with the real conductivity part are shown. Firstly a cylindrical object with 0.75 cm radius and 2 cm height placed vertically (which is far smaller than the objects tested in reference [5]) and 8 S/m of conductivity value. In the second case of figure 5, a cylindrical object with 2 cm radius and 4 cm height and 1.3 S/m was used. Acquisitions were done without averaging, which will be explored in the final version.

4. Conclusions and Further Work

Comparing with published work, this is as far as we know, the best minimum measurable SCR presented for a long time acquisition (maximum tested was 5 min approximately) that is, the best relation between resolution and applied current for a given frequency signal ($2.7 \cdot 10^{-7}$ for the average case). Also, a measurement examples using cylindrical biological ghosts show that the twin coils setup and the presented processing method is a feasible measurement method for biological MIT using moving sensors. In the final paper, besides the improvements referred on the previous chapter, the source current signal maximum amplitude will be also improved. A study about how the movement can affect these techniques will be presented, namely how the coil reference measures could affect the final reconstruction. Data from simulated results with the presented tested bodies will be compared with the obtained measures. Finally, the newly achieved measurement accuracies should be analyzed in detail in terms of the impact on the reconstruction abilities.
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