Electromagnetic coupling simulations for a magnetic induction sensor for sleep monitoring

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Abstract

Magnetic induction (MI) method has been extensively used in non-destructive testing of materials. In biomedical applications, it attracted lots of attention for the contact-less advantages it provides. Sleep monitoring through detecting conductivity changes in lungs and heart during breathing and cardiac activity is the purpose of our studies. The low conductivity of biological tissues increase the complexity of the design of such systems. One challenge is to separate the effects of magnetic field from the electric field; achieving a pure magnetic contribution is difficult since the received signal is contaminated by the unwanted capacitive coupling. Our hypothesis is that for a periodic vital sign monitoring like breathing and heart activity, part of this secondary coupling could be considered as a desired effect to take the advantage of both contributions. In this paper, the coupling mechanisms existed in our system have been simulated and studied using finite element and Orcad simulations to estimate different contributions we would have in the developed MI system.

1. Introduction

Magnetic induction (MI) is a well-known method that has been used in lots of applications such as non-destructive testing of materials, process industry, medical imaging, vital sign monitoring and food industry.

Based on Maxwell equations when a conductive object is placed in a time varying magnetic field, eddy currents are induced in the object which produce a secondary magnetic field. This field could be received by a sensor and it contains information about the dielectric properties of the sample.

In a practical MI system, the signal acquired is not only due to the magnetic field but also the electric field (capacitive coupling). In the majority of applications named above, especially those in which the sample to be monitored (characterized or imaged) has low conductivity or is non-magnetic, capacitive coupling could be considered as an unwanted signal which cause large errors and make the design of the system more complex. However in an application like breathing (vital sign) monitoring, part of the capacitive coupling maybe a desired signal, combining the advantages of both contributions: electric and magnetic.

Small movements of chest due to breathing cause a periodic small change in the distance between body and the sensors. This modify the signal in correlation with the breathing activity which together with the changes in conductivity –detected by the magnetic induction method- could lead to a higher quality received signal from breathing or other physiological activities. Moreover, it is not fully known that whether the capacitive coupling between the coils via the object, only reflects the outline and surface displacement of the object or it may have contributions from the internal structures too. The change in the distribution of charges changes the electric field and capacitance and it may change the resistive losses inside the object.

Nevertheless, knowing an approximation of each component's share in the received signal would be of interest for hardware design and interpretation of the received data. However eliminating or totally avoiding the so-called unwanted effect is impossible. We have studied and evaluated the magnetic and electric couplings for our vital sign monitoring MI system (previously described in [1] and [2]), whether the idea of considering the capacitive effect as a desired signal could improve the sensitivity of the system.

2. System description

The system is based on two coils as excitation and receiver coils and a phase sensitive detector. The excitation signal is provided by a signal generator at a frequency of 10.7 MHz. The received signal is amplified by a low noise amplifier and after filtering is introduced to a demodulator [1].

The planar coils are implemented in printed circuit board, suitable for being placed under the mattress. The receiver coil has been designed in a way to cancel the strong primary magnetic field since the secondary signal due to conductivity changes is very low in comparison.

The design is based on [3] and intend to integrate approximately the same amount of flux from primary field but in the opposite sign. As a result it could act similar to a gradiometer and subtract the large background voltage from the direct magnetic coupling.

Coil configuration used in the system is shown in Figure 1. The coils are readjusted in the absence of the object to achieve the minimum voltage. Since the distance between the subject and the coil is important to remain constant, the sensors are placed under the rigid structure of the bed base. An image of the experimental setup is shown in Figure 2 .

In the experiments for breathing and cardiac signal detection, a pulse plethysmogram and a respiratory effort transducer (from a BIOPAC-MP36 system) were added to the system as reference.

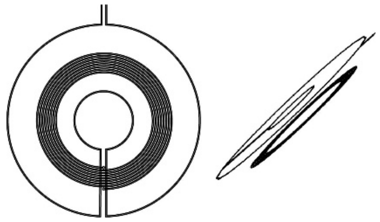

Figure 1. *Coil configuration in the developed MI system*

Figure 2 *Experiment setup (saline solution over the sensors)*

3. Coupling mechanisms

As stated, since in some applications receiving the true magnetic induction signal is of particular interest, the contamination of the MI signal by capacitive coupling and its effects on the received signal has been studied by several groups [4] and the coupling mechanism are well explained [5]. The main capacitive paths are the direct capacitive coupling between the source and the receiver coils and the coupling via the sample. The former can cause a large background voltage in-phase or 180º out of phase with the excitation coupling and the latter can cause changes in received signal (in-phase and quadrature) components [5]. However, there are other sources of coupling paths and they are also dependent on other parameters such as geometry of the coils or the object and generally difficult to model or measure directly. Electrostatic screening and careful grounding are common recommendations for avoiding the unwanted capacitive coupling.

Attention has to be given to the screening type since in different applications the screening could have reverse effects. For example, in our MI system the coils have small number of turns and implemented in PCB so a comb screen applied to suppress the direct electric field coupling without the presence of any object. The screen consists of a set of parallel copper strips connected together to have the same electrical potential and cut to prevent the circulation of eddy currents. If the screen works as desired, it has to reduce the electric field effect and has no or very small effect on magnetic coupling. The experiments show that the presence of the screen, not only did not suppress the capacitance but also increase it in a way that the adjustment of the coils to achieve a minimum background voltage was not possible anymore. Simulations are in accordance with these experiments and will be explained later in this paper. In addition, a set of practical tests recommended in [5] have been applied to determine the significance of the capacitive and magnetic coupling. In this paper only the simulation results are presented.

4. Coupling simulation

Although as stated before, modeling and measuring all of the elements and equivalents of such a MI system is not completely possible, a simplified model of the equivalent circuit has been simulated with Orcad for the coupling case mentioned above. In addition, an electrostatic-electromagnetic study has been run with COMSOL multiphysics in order to find an approximation of capacitance values which exist in each coupling path. The electrostatic simulations show (as expected) the higher value of capacitance is by direct coupling between the excitation and receiver coils through the sample. Moreover, the effect of the distance between the target and coils vs. the effect of changing the conductivity has been checked in these simulations. *Figure 3* shows the model used for simulations.

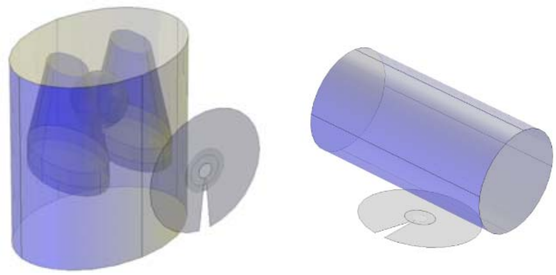

Figure 3. *Models used for electrostatic, electromagnetic simulations*

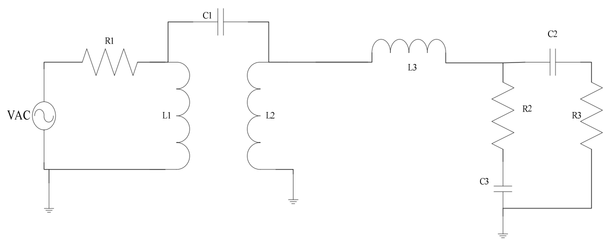

Figure 4. *Equivalent circuit for direct capacitive coupling between excitation and detection coil*

5. Results and discussion

5.1. COMSOL Simulations

- ***Electrostatic Simulations***

The approximate values for capacitance between the coils and between coils and the target (body) in a simplified model of the system, was calculated by COMSOL. According to the electromagnetic simulations the maximum capacitance as expected is by the direct coupling from coil to the body (large surface) and is about 0.2 nF. The capacitance between two coils (Exc-Det) is smaller (about 10 pF). Using electrostatic simulations, considering the case having the maximum potential possible of the system over excitation coil (3.3 V), the potential in the receiver coil (in presence of the sample) would be around 110 mV.

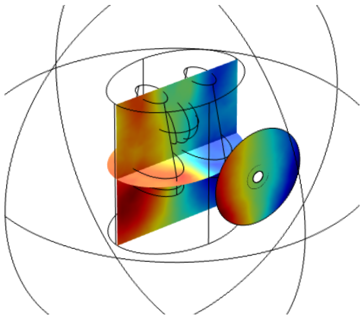

Figure 5. *Graph of electric potential (electrostatic simulations)*

- ***Magnetic Simulations***

Another set of studies were the simulations regarding the response of the system to different saline solutions in order to compare later with the experimental results. As it could be seen in Figure 6 the linear relation between imaginary and real part of the detected signal until a certain conductivity means that there is no other coupling apart from the magnetic one (which is true since this section of simulation is magnetic only). The linearity decrease when approaching to conductivities more than 1 S/m which is the limit for validity of skin depth. Because in our case, considering the sample's thickness (15 cm) we are limited to use solutions with conductivities up to 1 S/m. Figure below shows the skin depth for different saline solutions and the reference line is the dimension of the sample.

In addition to the mentioned studies, the sensitivity of the system to vertical displacement has been also studied for later experimental use to make sure of the sources of the changes in the signal, whether they are due to capacitive effect or it is just the effect of displacement regarding the coils.

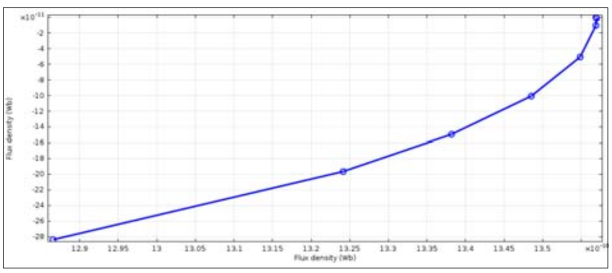

Figure 6. *Imaginary vs. real part of the detected signal for different conductivities (0, 0.01, 0.1, 0.5, 1, 1.5, 2, 3 S/m)*

Displacement sensitivity simulation results show that by a shift of 5 cm to right (or left) regarding the coils, the signal decrease about 25%. This value for a shift of 9 cm is around 55% and the signal drops to half of its value in comparison with the time when it is centered.

It could be say that the safe region for horizontal displacements could be maximum of 10 cm (5 cm to each side of the coils).

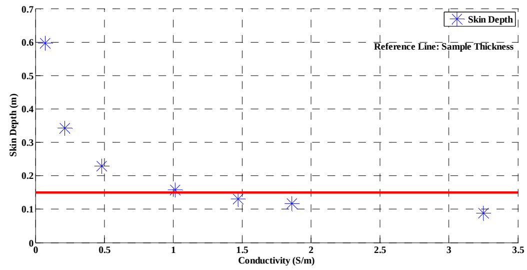

Figure 7. *Skin depth for different solutions vs. sample thickness*

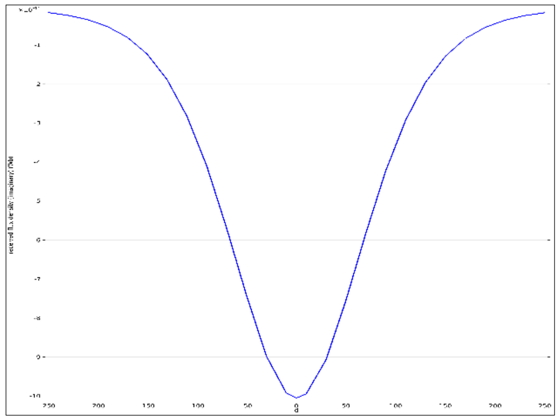

Figure 8. *Sensitivity of the system to horizontal displacement regarding the sensors (0 is the center of the coil)*

5.2. ORCAD simulations

Using the equivalent circuit of *Figure 4* and assuming a capacitance of 0.05 pF between two coils, the frequency response and behavior of the system with different coupling factors and capacitors was studied.
Figure 9 shows the residual voltage due to presence of the C1 (direct capacitive coupling between two coils). Considering C1=0.05 pF, at 10.7 MHz the minimum voltage obtained (34.48 μV) when the coupling factor is -0.75. The simulation was repeated for other values of C1 and the results are shown in Figure 9 and Figure 10. *Table 1* shows the minimum residual voltage obtained at 10.7 MHz for different coupling factors and capacitors.

C1 (pF)	Minimum voltage	Coupling Factor
0,05	34,5 μV	-0,075
0,5	2,58 mV	-0,001
1	5,59 mV	-0,001
10	62,49 mV	-0,001
100	1,32 V	-0,001

Table 1. *Minimum residual voltage due to different capacitance and coupling factors*

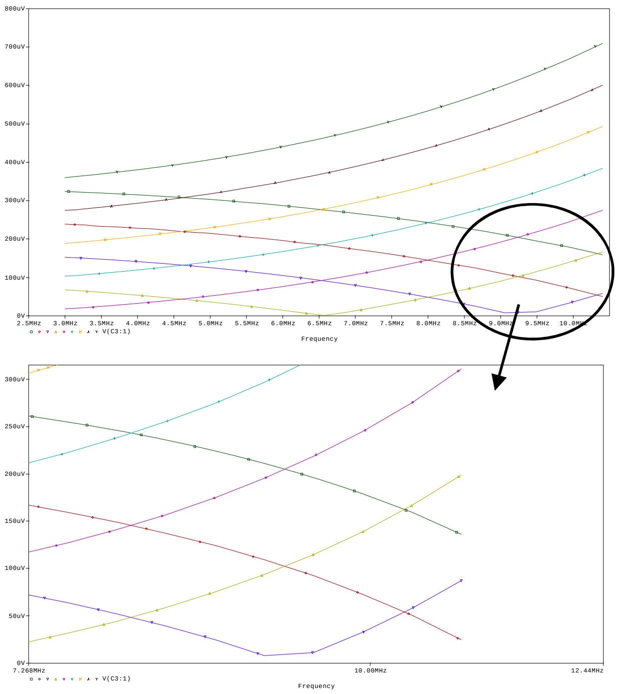

Figure 9*. Resdiual voltage for various coupling factors, C1=0.05* ***pF***

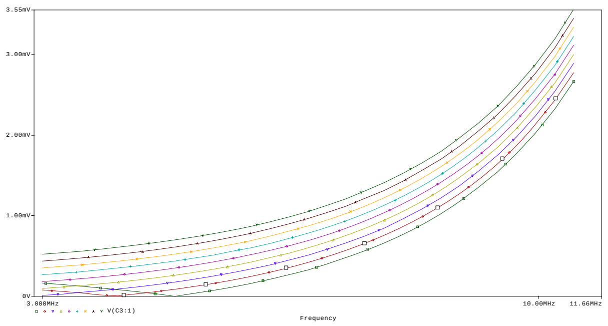

Figure 10. *The residual voltage graph for C1=0.5* ***pF***

From the result of the Orcad simulations it could be concluded that:

a) There would be always a minimum residual voltage due to this capacitive coupling and it could not be eliminated.

b) Suppressing or minimizing this effect could be done only in certain direction of the magnetic field since according to the results the minimum voltages obtained while the coupling factor was negative.

c) As stated before, there are some known methods for minimizing the effect of capacitive coupling but one has to take in account that some of those methods will add capacitance to the existing coupling and make it even more difficult to suppress or eliminate the effect.

Future works will be partly focused on simulations of coupling via the object and also presenting the experimental results obtained for the MI system.

References

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